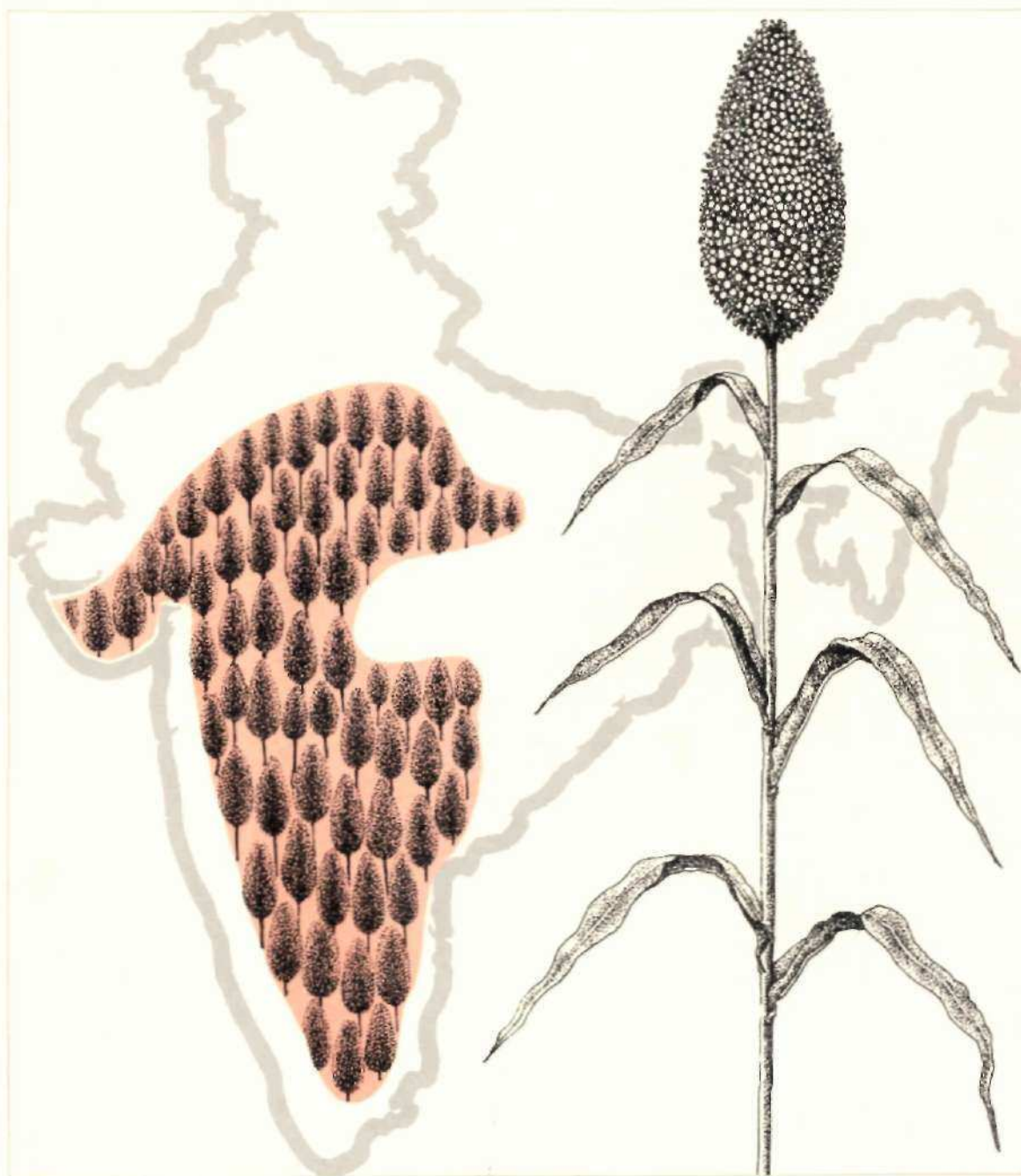


A Review of Fertilizer Use Research on Sorghum in India



**Research Bulletin no. 8
International Crops Research Institute for the Semi-Arid Tropics**

Abstract

Tandon, H.L.S., and Kanwar, J.S. 1984. A review of fertilizer use research on sorghum in India. Research Bulletin no.8. Patancheru, A. P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

This literature review, which covers the period 1960 to 1983, is concerned with the response of grain sorghum to all soil nutrients, related soil and climatic conditions, and the seasons in which the crop is grown. The main objective is to quantify the responses and their relationship to different environments. However, the results clearly demonstrate the widespread deficiency of nitrogen (N), phosphorus (P), and zinc (Zn) under both rainfed and irrigated conditions. High-yielding cultivars have shown greater responses than local cultivars and, invariably, both N and P have shown additive effect. Split application of N is generally more efficient than a single-dose application. When the ^{15}N technique is used it has been observed that about 62.5% fertilizer N is recovered by sorghum from Alfisols and 55% from Vertisols. Drilling of phosphate proved more efficient than broadcasting. The responses to potassium (K) are rather rare, except in long-term experiments. Responses to the application of Zn are reported, especially in Vertisols when the available Zn is about 1.0-1.2 ppm or less. In the post-rainy-season crop the responses to N are dependent on the nature of the cultivar and the nitrate-N level of the soil. The optimum level of nitrogen for sorghum varies from 60 to 120 kg/ha N in the rainy season, 25 to 85 kg/ha N in the post-rainy season, and 80 to 150 kg/ha N in the summer season. A finding of the review is that most of the publications reviewed report the results of the so-called rate-and-date type of agronomic research. Little effort appears to have been made to quantify the relationship of fertilizer responses to soil fertility and environments. Though responses to N and P, under both rainfed and irrigated cropping conditions, show that fertilizer use is the key for increasing production, few research data are available on nutrient x moisture interactions and their management.

Resume

Tandon, H.L.S., et Kanwar, J.S. 1984. (Synthese de la recherche realisee en Inde sur l'utilisation de l'engrais pour le sorgho). A review of fertilizer use research on sorghum in India. Research Bulletin no.8. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

Cette synthese, couvrant la periode 1960 a 1983, traite la reponse du sorgho grain a tous les elements nutritifs du sol, aux conditions pedo-climatiques relatives et aux saisons de culture. L'objectif principal est de quantifier les reponses et leurs rapports avec des differents milieux. Cependant, les resultats mettent en evidence une carence generalisee en azote (N), en phosphore (P) et en zinc (Zn) en conditions de culture pluviale et irriguee. Les cultivars a haut rendement ont donne de meilleure reponse que les cultivars locaux. N et P ont toujours montre un effet additif et N fractionne en bande a ete generalement plus efficace qu'un apport de N en une fois. On a observe que l'utilisation de l'azote 15 a permis l'importation d'environ 62,5% de l'engrais azote par le sorgho des Alfisols et 55% des Vertisols. L'efficacite de la fumure phosphate incorporee s'est averee superieure qu'a l'application a la volee. La reponse a l'engrais potassique (K) n'est observee que rarement, sauf dans les essais a long terme. Il y a eu de reponse a la fumure Zn, en particulier dans les Vertisols lorsque le zinc assimilable est de 1,0-1,2 ppm ou moins. A la campagne d'automne, la reponse a l'engrais azote depend du cultivar et du niveau du nitrate d'azote du sol. Le niveau optimum de l'azote pour le sorgho varie de 60 a 120 kg/ha de N a la saison des pluies; de 25 a 85 kg / ha de N a la campagne d'automne; et de 80 a 150 kg/ha de N a la campagne d'ete. La synthese a revele que la plupart des publications passees en revue ne fournissent que les resultats de la recherche agricole sur le dosage et l'epoque de l'apport d'engrais. Tres peu d'etude a ete realisee sur la quantification des relations des reponses aux engrais avec la fertilite du sol et les milieux. Les reponses a N et P indiquent que l'utilisation de la fumure est la clef pour augmenter la production agricole tant en conditions de culture pluviale qu'irriguee. Cependant, on dispose de peu d'informations sur les interactions entre les elements nutritifs et les ressources hydriques ainsi que leur gestion.

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A Review of Fertilizer Use Research on Sorghum in India

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FOREWORD

With the exponential growth in scientific literature, there is a need to synthesize the proliferating fragmented knowledge appearing in many different scientific journals and reports. While a bibliography provides a head-count of the total number of scientific contributions in a field of research, it does not give an idea of the growth of knowledge in that field, or the areas where more research efforts are needed. Reviews that sift, evaluate, and put each significant contribution into its proper perspective are increasingly seen as offering a possible path out of the literature jungle.

State-of-the-art reports that are reviews on selected, specific topics of active current interest are very useful for busy scientists. Preparation of these reports, however, requires close cooperation between documentalists and expert scientists—a combination not always possible to achieve. SMIC, the Sorghum and Millets Information Center at ICRISAT, was fortunate to have the willing cooperation of Dr. H.L.S. Tandon of the Fertiliser Development and Consultation Organisation, New Delhi, and Dr. J.S. Kanwar, Director (Research), ICRISAT, both renowned soil scientists, who agreed to write this bulletin.

Sorghum is the third most-widely grown crop in India after rice and wheat, and constitutes the staple food for a large proportion of the population. In this bulletin, soil fertility and fertilizer-use research on grain sorghum in India has been reviewed for the post-1960 period. The review covers all nutrients, soil-climate conditions, and seasons in which sorghum is grown. The reviewers studied many documents and used those which were considered to have made significant contributions to knowledge in the preparation of this review. I congratulate them and the documentalists of SMIC for the excellent work they have done.

L.D. Swindale
Director General
ICRISAT

PREFACE

The destiny of nonirrigated agriculture in India is closely linked with the attainment of increasing sorghum production. Sorghum is not only the most widely grown crop of the Indian semi-arid tropics (SAT) but it is also a staple diet for some 70-80 million people. Sorghum grain yields of 5-6 t/ha repeatedly obtained in research plots, and of 3-4 t/ha in on-farm trials, provide a glaring contrast with All-India average yields of 0.7 t/ha.

In major sorghum-growing soils, the deficiencies of nitrogen, phosphorus, and zinc are widespread. They keep grain yields at pathetically low levels. For every tonne of grain 61 kg of NPK are removed from the soil. Thus there is no way of increasing yields without the application of fertilizers. Thus fertilizer is the key to increasing production and much more so with the modern sorghum-production technology. In general, fertilizer use over much of the sorghum area is very low. It is a vicious circle, in which low consumption of fertilizers causes low yields and low returns to farmers thereby perpetuating poverty and use of less productive technology.

Sorghum is one of the five mandate crops of ICRISAT. In any enlightened research program the need for stock-taking exercises on the accomplishments, missing links, and future research needs is appreciated. This review is a stock-taking exercise with a three-fold objective: (i) to review the quantum and type of research data available, (ii) to attempt an interpretation and synthesis of the scattered information available, and (iii) to identify areas of future research. Over 600 published papers formed the information base for this state-of-the-art report.

We have thought it appropriate to organize available information into independent sections on rainy-season sorghum (10 m. ha) and the postrainy-season sorghum (6.5 m. ha). Meager research on the postrainy-season sorghum is glaringly evident. In this review, all plant nutrients whether termed macro or micro have been discussed. Published data from research stations as well as from experiments conducted on cultivators' fields have been taken into account. An attempt has been made to interpret fertilizer responses in terms of different factors such as genotypic differences, soil analysis, moisture, rainfall, and nutrient uptake. The last section contains some suggested areas for future research, arising largely from the preceding sections.

While preparing this review, we have felt that a multidisciplinary approach in experimentation and/or data interpretation was generally missing, both in letter and spirit. Thus although general trends and nutrient responses are known, the measurable factors affecting these responses or a multifaceted in-depth understanding of the soil profile/weather/sorghum/fertilizer system is not yet available. This review has not recognized the boundaries between different projects and institutes carrying out research on sorghum. It has tried to integrate available information on grain sorghum considering it as an All-India resource to be continuously refined and built upon in future.

As ICRISAT is a world center for research into the crop production problems of the semi-arid tropics, this review in a way heralds the end of the beginning in this area of activity. It adds a new dimension to the work of the Sorghum and Millets Information Center (SMIC). We believe that reviews will be urgently needed for other important crops and agroecological zones on a global basis as well. This review is confined to India but, recognizing the interest of many francophone countries in the sorghum crop, the abstract has also been given in French.

Finally, preparation of this review has generally been a satisfying exercise. It will be particularly satisfying to see large numbers of SAT farmers using improved practices, including the application of fertilizer, which is the kingpin of any strategy for increasing sorghum yields and improving the well-being of SAT farmers.

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Acronyms and Abbreviations

AICARP	All India Coordinated Agronomic Research Project
AICRPDA	All India Coordinated Research Project for Dryland Agriculture
AICSIP	All India Coordinated Sorghum Improvement Project
CSH	Coordinated Sorghum Hybrid
CSV	Coordinated Sorghum Variety
DES	Directorate of Economics and Statistics
ENSP	European Nitrogen Service Programme
FAI	Fertiliser Association of India
HYC	High-yielding Cultivar
IADP	Intensive Agricultural District Programme
IARI	Indian Agricultural Research Institute
IASRI	Indian Agricultural Statistics Research Institute
ICAR	Indian Council of Agricultural Research
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
LER	Land Equivalent Ratio
NCA	National Commission on Agriculture
NCAER	National Council of Applied Economic Research
SAT	Semi-Arid Tropics
SMIC	Sorghum and Millets Information Center

Terminology

1. Botanical name: *Sorghum bicolor* (L.) Moench.
Hindi name: jowar. Tamil name: cholam.
2. High-yielding varieties, with hybrids and synthetics, have been collectively referred to in the text as high-yielding cultivars (abbreviated HYCs).

Acknowledgments

During the preparation of this review we benefitted from discussions with many research workers. A number of scientists gave us reprints and useful background information about the results published by them. The number of these helpful colleagues working in agricultural universities, institutes, the ICAR system, and at ICRISAT is indeed large. We are grateful to each one of them. We also record our gratitude to S. Dutta and his colleagues in the Sorghum and Millets Information Center for collecting the documentation, and to S.M. Virmani, Leader, Farming Systems Research Program, ICRISAT, for coordinating this project.

1. SCOPE, COVERAGE, AND METHODOLOGY

1.1 Introduction

Sorghum is the third most widely grown crop in India after rice and wheat. However, it is the most important crop of the semi-arid tropics (SAT) in India and constitutes the staple food for a large proportion of the population. High priority is therefore attached to research programs aimed at improving the crop's grain yields.

This bulletin is an analytical review of reported research in India on soil fertility and fertilizer use in the cultivation of sorghum. The authors' objectives are three-fold: (1) to take stock of the research information available on the subject; (2) to interpret available data concerning nutrition and yield and draw inferences for practical application; and (3) to identify the gaps or weak points in available information with a view to recommending areas for future research.

1.2 Scope

The review is confined to research on grain sorghum because sorghum is grown primarily for the grain that is consumed as food in the semi-arid tropics of India. Research efforts in sorghum are also primarily aimed at improving grain yields. Literature citations are from 1960 onwards, because much research in India has taken place since that year and the data given include results obtained in the use of high-yielding cultivars (HYCs), the first hybrid (CSH 1) having been released in 1964 (Appendix 1). Citations include all nutrient elements—primary, secondary or micro—and cover the three seasons in which sorghum is grown: the rainy season (kharif), the post-rainy season (rabi) and the summer (dry) season. Publications giving data from research stations and experiments on farmers' fields comprise important citations for this review. A study of the literature shows that soil fertility aspects have received far less attention than field responses of sorghum to fertilizer applications. This reflects the emphasis given by sorghum researchers to fertilizer experiments—an emphasis that may now need reorientation, as is suggested in later sections.

1.3 Literature Coverage

Over 600 papers were studied, of which only those considered to have made an identifiable contribution to knowledge on the subject have been cited. Priority was given to well-conducted field experiments repeated over several years and supported by basic information on soils, agronomy, and agroclimatology. Reports

based on solution/sand/pot cultures were included where these employed special techniques, scarce materials, or required controlled conditions for precision measurement. Generally, single-season "yield-only" field trials, without supplementary information about the system, or "first information reports" such as those found in the *Sorghum Newsletter*, were included only in exceptional cases. Background details of published research were obtained through correspondence with individual authors, where necessary, and it has therefore been possible to include in the review data that are not available in the publications cited.

1.4 Methodology

Research information has been reviewed in independent sections for different seasons. Topics of overall interest have been brought together and presented in section 4.1.

A recurring feature in published information is the unexplained variability in fertilizer response data. Differences for the same cultivar and location often exceed the "classical" differences between traditional and high-yielding cultivars. It is easier to average the results than to explain them. For instance, in many cases, reported results are averaged over the very treatments (cultivars or N levels) that were meant to be tested; field experiments are terminated after one season; supporting soil, plant, and weather analysis data are not reported. Inadequate information on nutrient uptake and on preceding crops adversely affects the interpretation of available data; blanket applications of 10-25 t/ha farmyard manure are given to nitrogen experiments; phosphorus is studied on sites not responsive to P; plot sizes in field experiments can be less than 5 m²; variability can render yield differences of more than 1 t/ha statistically nonsignificant; and the expressions P, P₂O₅, phosphorus, and phosphate are used casually. In research with the post-rainy-season sorghum, moisture in the soil profile at seeding is rarely reported. However, many of the above features are not confined to sorghum research alone but are general features of fertilizer-use research in India (Tandon 1980).

Two noteworthy features of sorghum research have been: (1) the rapid evaluation of new genotypes for their fertilizer responsiveness in multilocation trials since the mid-1960s; and (2) fertilizer research has been a part of the overall multidisciplinary research effort concerning dryland agriculture, also in multilocation trials over the past 10-15 years. However, soil-fertility research has not received the attention it deserves.

2. AREA AND PRODUCTIVITY OF SORGHUM

Sorghum is the most important grain crop of nonirrigated areas of the semi-arid tropics in India, and it is grown over 16.5 million ha (DES 1981). It is cultivated largely as a grain crop for direct human consumption. Sorghum as a forage crop is also important, especially in north and northwestern India, but precise statistics on the area under forage sorghum are not available. Sorghum stover is a valuable fodder for cattle and is a particularly valued output in the postrainy season. It is also not possible to determine the area under different sorghum-based cropping systems.

2.1 Area

During the past 30 years the area under sorghum has not changed more than $\pm 10\%$ of the current figure of 16.5 million ha. In the early 1950s, the area under sorghum exceeded the area under wheat by 6 million ha. In 1984 the reverse applies.

The rainy and the postrainy seasons account for nearly 10 and 6.5 million ha of sorghum area respectively, the latter also including about 500 000 ha under the summer crop. Distribution of sorghum area between the two main seasons, based on district-level statistics, is depicted in Figures 1a and 1b. The areas in which rainy-season¹ and postrainy-season sorghum cultivation predominates are fairly clearly indicated.

1. For India as a whole, 74% of the mean annual rainfall is received during the June-September period, being 90% in Madhya Pradesh, 85% in Maharashtra, 66% in interior Karnataka, and 23% in Tamil Nadu.

Sorghum cultivation in India has identifiable areas of concentration. While the crop may be grown in nearly 200 districts, 75% of its area is located in 53 districts, 50% in 24 districts, and 25% in only 8 districts (Solapur, Ahmednagar, Osmanabad, Bijapur, Pune, Aurangabad, Parbhani, and Bhir). All these districts, except Bijapur, are in Maharashtra state, and postrainy-season sorghum is the predominant crop. It is grown mostly on Vertisols and Vertic (black soil) types.

Nearly 80% of the total area under sorghum is in the four states of Andhra Pradesh, Karnataka, Madhya Pradesh, and Maharashtra (Table 1). In Madhya Pradesh sorghum is entirely a rainy-season crop, but in the other three states it is almost equally divided between the rainy and the postrainy seasons. These states account for 95% of the total area under postrainy-season sorghum in India. Gujarat, Rajasthan, Tamil Nadu, and Uttar Pradesh are the other important sorghum-growing states, where most of the sorghum is cultivated as a rainy-season crop. In Haryana, Rajasthan, and Uttar Pradesh much of the crop is grown for forage.

Ninety-five percent of the sorghum area in India receives no irrigation (Table 1). The rainy-season crop is primarily rainfed, while the postrainy-season crop is mainly dependent on the moisture stored in the soil profile, supplemented by any rains received during crop growth.

2.2 Grain Yields

Data trends in the area and yield of sorghum shown in Figure 2 indicate a small gradual improvement in the

Table 1. Area, production, and yield of sorghum in India (1979-80).

State	Area sorghum irrigated ¹ (%)	Area		Production		Yield (t/ha)			
		(million ha)	Rainy season (%)	Postrainy season (%)	(million t)	Rainy season (%)	Postrainy season (%)	Rainy season	Postrainy season
Andhra Pradesh	1.4	2.35	43	57	1.63	42	58	0.68	0.70
Gujarat	4.2	0.95	82	18	0.56	73	27	0.53	0.85
Haryana	23	0.13	100	0	0.03	100	0	0.22	0
Karnataka	7.5	1.97	46	54	1.67	62	38	1.16	0.58
Madhya Pradesh	neg.	1.91	99	1	0.95	99	1	0.50	0.50
Maharashtra	5.4	6.83	44	56	5.46	63	37	1.13	0.53
Rajasthan	0.1	0.86	100	0	0.15	100	0	0.18	0
Tamil Nadu	12.8	0.71	83	17	0.69	81	19	0.95	1.05
Uttar Pradesh	1.0	0.69	100	0	0.16	100	0	0.22	0
All India	4.59	16.45	60	40	11.32	66	34	0.75	0.60

Source: DES 1981

1. Area irrigated pertains to 1976-77 (FAI 1981). A significant area in Gujarat, Haryana, Rajasthan, and Uttar Pradesh may be devoted to fodder sorghum

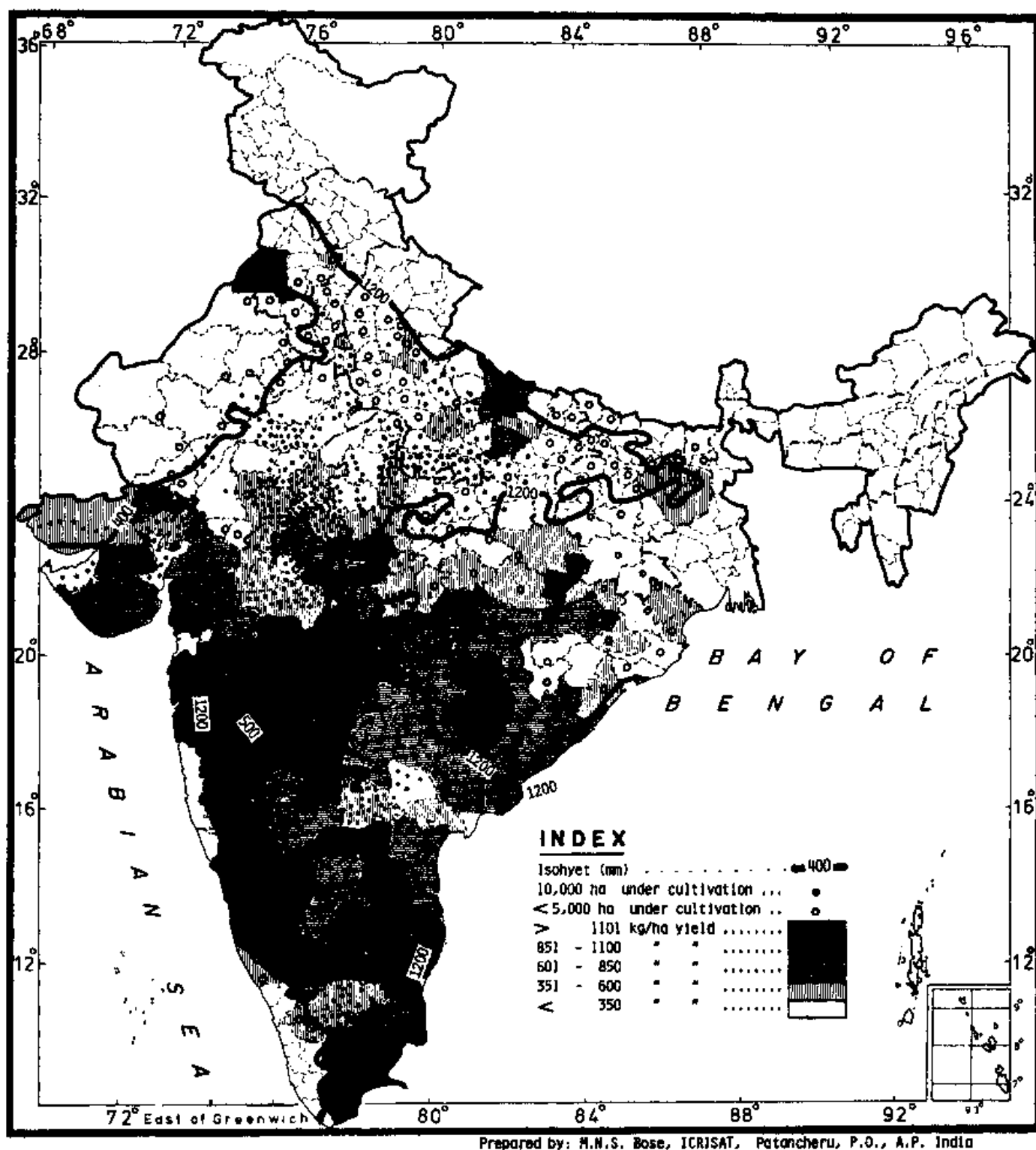


Figure 1a. Rainy-season sorghum in India: area and yield map (1979-80).

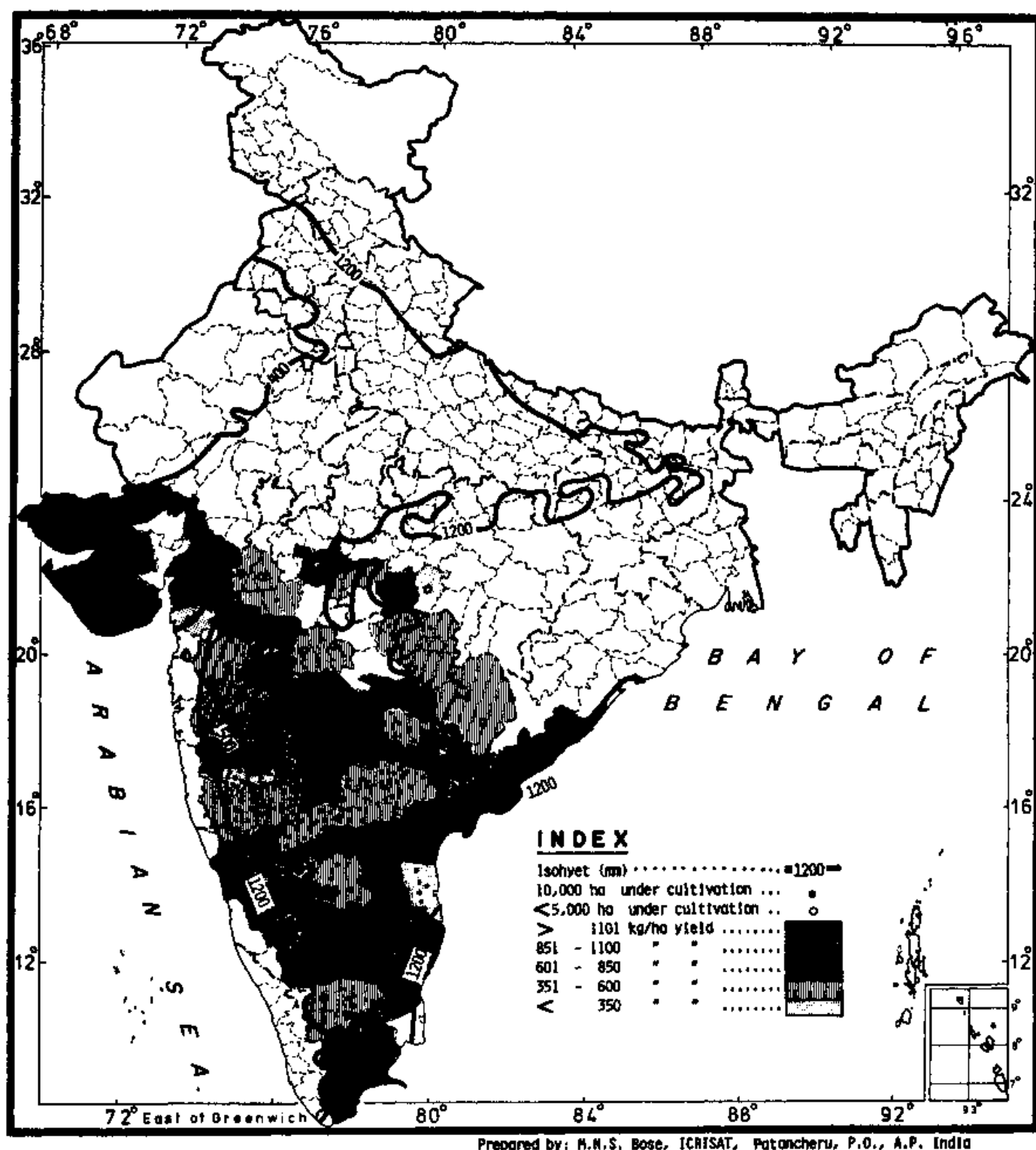


Figure 1b. Postrainy-season sorghum in India: area and yield map (1979-80).

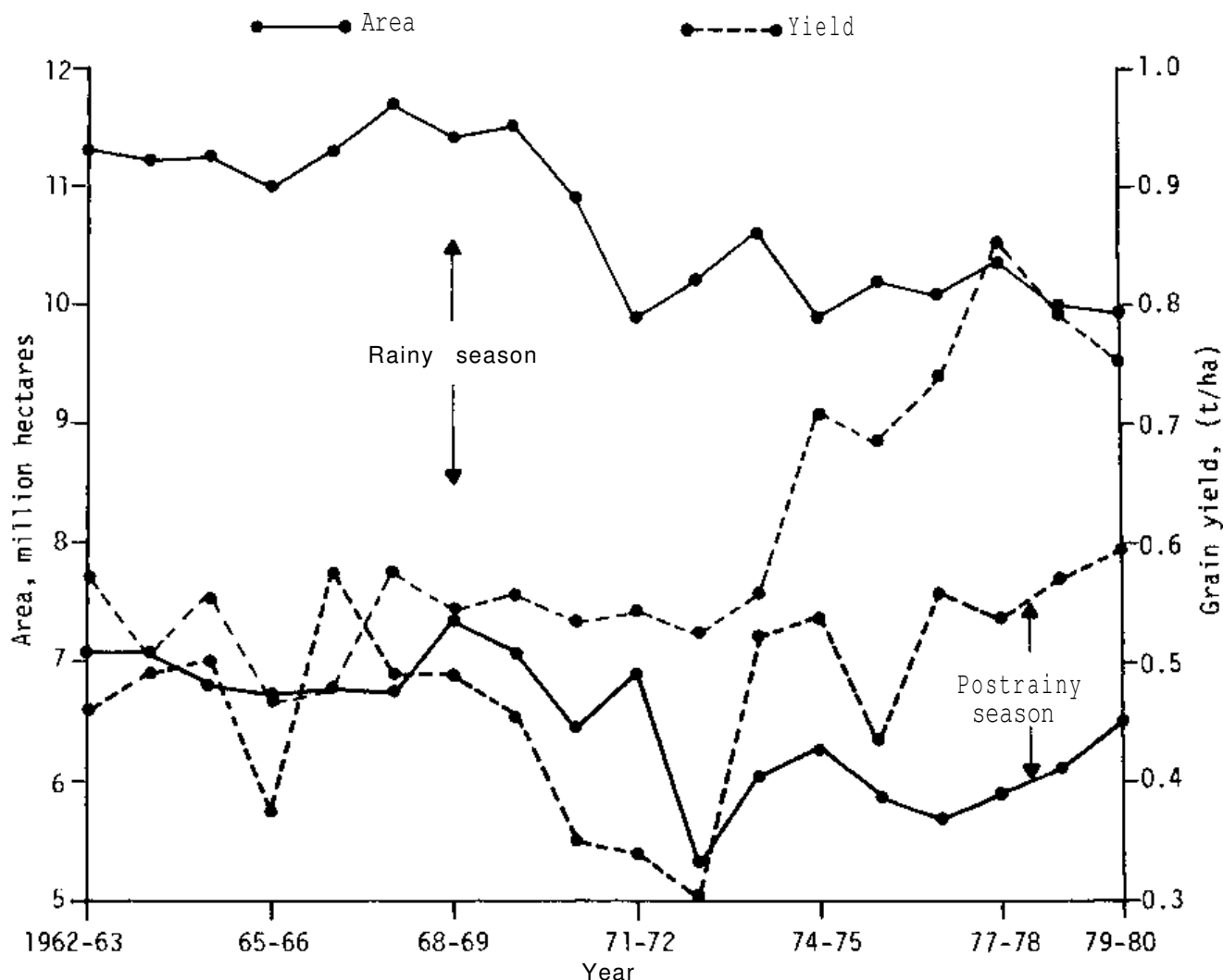


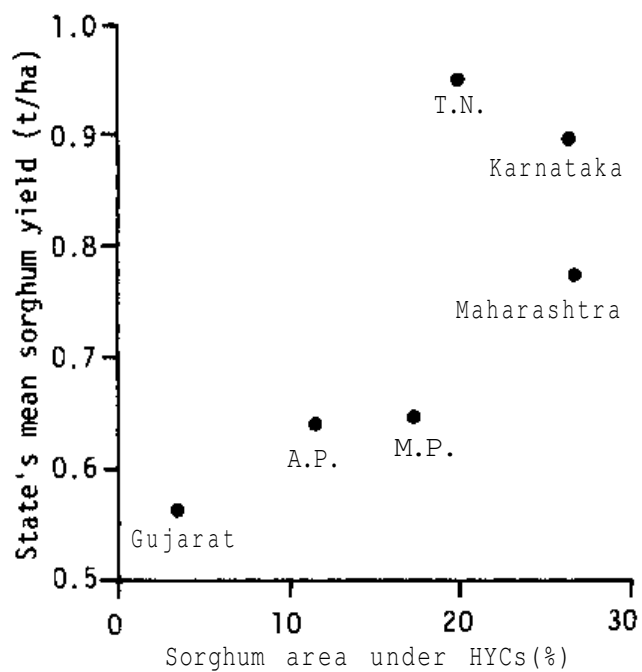
Figure 2. Changes in the area and yield of sorghum in India over several years in the rainy and postrainy seasons. (DES 1981.)

yield of rainy-season sorghum over the years. Overall yields have increased from 0.4 t/ha to 0.7 t/ha in 30 years. Although grain yields continue to be dismally low, in order to obtain a realistic estimate of sorghum yields the fodder area must be deducted from the total sorghum area. This requirement may account for the extremely low grain yields in Haryana, Rajasthan, and Uttar Pradesh given in Table 1.

Data presented graphically in Figure 3 suggest, tentatively, that average sorghum yields are higher in states where the cultivation of HYCs is more widespread than that of other cultivars. The top yield position of Tamil Nadu, however, is a combined effect of the spread of HYCs and irrigation (15% of the sorghum area), the latter figure being the highest among the sorghum-

growing states. Since 1964, when the first hybrid (CSH 1) was released for cultivation, approximately 25% of the sorghum area is estimated to have been planted with HYCs (hybrids and improved varieties). In the early 1980s the area planted to sorghum HYCs is estimated to be rapidly increasing in some states, particularly in Maharashtra.

Attention is called to the observable yield gap between average data for sorghum grain yield in the early 1980s of 0.7 t/ha, and proven potential of 3-4 t/ha on Alfisols, and up to 5.5 t/ha on Vertisols. These data apply to dryland agriculture, without irrigation, and the high potentials are derived from numerous field trials averaged over many years (IARI 1979; Kanwar 1982; Randhawa and Venkateswarlu 1980).



The areas with the greatest potential for increasing the production of rainfed sorghum are considered to be western Madhya Pradesh, the western Vidharba and Marathwada regions of Maharashtra, the late rainy-season (maghi) region of Andhra Pradesh, and the Dharwar region of Karnataka (ICAR 1980).

Figure 3. Association between the spread of HYCs and sorghum yield: mean of 1977-80. (Tamil Nadu and Karnataka have higher proportions of sorghum area under irrigation. DES 1981; FAI 1981.)

3. SORGHUM-GROWING SOILS, THEIR FERTILITY, AND THE STATUS OF FERTILIZER USE

3.1 Soils

As shown in Figures 1a and 1b, sorghum is grown throughout the Indian SAT. Rainy-season sorghum is grown under wide-ranging agroclimatic conditions in Vertisols, Vertic soil types (Entisols, Inceptisols), and to a certain extent in Alfisols. Postrainy-season sorghum is largely confined to Vertisols. A recent account of the soils of the semi-arid tropics is available (Murthy et al. 1982, Swindale 1982). Characteristics of selected benchmark profiles from sorghum-growing areas are given in Table 2. Deficiencies of N, P, and Zn are considered to be widespread, and of practical importance for improving sorghum yields (Finck and Venkateswarlu 1982; Kanwar 1982; Rao and Das 1982; Virmani et al. 1982a).

3.2 Soil Fertility

Soil fertility research specifically concerning sorghum is rather limited. A general picture of the fertility status of 158 sorghum-growing districts for N, P, and K, however, is provided in Table 3. The low N-supplying capacity of soils in the Indian SAT is also reflected in the 0.5-1.0 t/ha overall grain-yield levels. At an assumed 4% rate of net mineralization of organic matter, availability of 50 kg/ha N per year in the top 30 cm of a soil containing 0.03% total N has been mentioned (Dart and Wani 1982). Experimentally-determined estimates of N mineralization and its release in Indian SAT conditions are not yet available. Additions through rainfall and non-symbiotic fixation in the SAT are estimated at 5 kg/ha N per year (cited by Vlek et al. 1981), though data specifi-

Table 2. Selected characteristics of some benchmark soil profiles from sorghum-growing areas.

Horizon (depth in cm)	PH (1:2.5 H2O)	Particle size (%)			O.C. (%)	C.E.C. (me/100 g)	DTPA-Zn (ppm)
		Sand	Silt	Clay			
Typic Chromustert Sarol Series, Indore, Madhya Pradesh							
AP (0-11 cm)	8.0	13.4	30.5	56.1	0.40	53.2	0.29
A 12(11-29)	8.1	10.6	31.5	57.9	0.34	44.9	0.27
A 13 (29-54)	8.1	8.3	33.6	58.1	0.34	57.2	0.24
A 14 (54-95)	8.1	6.0	35.0	59.0	0.30	58.1	0.25
A 15(95-119)	8.1	7.9	36.6	55.5	0.30	45.2	0.28
A 16 (119-147)	8.2	10.0	38.0	52.0	0.27	49.2	ND
AC (147-160)	8.2	9.4	38.1	52.5	0.27	43.5	ND
Udic Chromustert Linga Series, Nagpur, Maharashtra							
AP (0-16 cm)	8.3	4.8	20.6	74.6	0.51	59.3	0.44
A 12 (16-47)	8.1	5.5	20.0	74.5	0.47	56.0	0.22
A 13(47-84)	8.1	9.7	16.5	73.8	0.42	64.2	0.26
A 14 (84-117)	8.1	10.3	15.1	74.6	0.49	69.4	0.26
AC (117-140)	8.1	10.1	19.0	70.9	0.27	65.1	ND
Typic Chromustert Barsi Series, Solapur, Maharashtra							
AP (0-12 cm)	8.5	8.6	25.5	65.9	0.53	70.1	0.26
A 12 (12-36)	8.4	7.2	28.5	64.3	0.52	57.2	0.25
A 13(36-69)	8.3	7.0	24.0	69.0	0.50	65.4	0.20
A 14 (69-114)	8.4	2.8	21.0	76.2	0.53	57.5	0.28
AC (114-147)	8.4	10.3	18.6	71.1	0.39	66.8	ND
C (147-167)	8.2	18.1	23.5	58.4	0.26	64.6	ND
Udic Rhodustalf, Patancheru series, Medak, Andhra Pradesh							
AP (0-10 cm)	6.5	73.0	9.1	17.9	0.84	8.1	ND
A 12(10-20)	6.5	72.5	9.1	18.4	0.79	8.4	ND
B 1 (20-30)	6.7	58.2	9.3	32.5	0.85	14.6	ND
B 21t (30-49)	6.7	56.9	8.6	34.5	0.85	15.1	ND
B22t(49-102)	7.8	53.1	7.4	39.5	0.48	17.0	ND
BC (102-145)	7.0	61.9	13.8	24.3	0.23	22.2	ND

Continued

Table 2 continued

Horizon (depth in cm)	PH (1:2.5 H2O)	Particle size (%)			O.C (%)	C.E.C. (me/100 g)	DTPA-Zn (ppm)
		Sand	Silt	Clay			
Typic Pellustert, Kasireddipalli series, Medak, Andhra Pradesh							
AP (0-20 cm)	8.8	23.5	22.8	53.7	0.73	57.2	1.27
A 12(20-40)	9.2	21.7	21.6	56.7	0.54	58.5	0.29
A 13(40-60)	9.4	19.5	22.1	58.4	0.47	56.1	0.26
A 14(60-90)	9.4	16.2	23.7	60.1	0.39	60.0	0.21
AC (90-130)	9.4	11.6	21.0	67.4	0.28	62.9	0.21
C (130-180)	9.4	12.9	20.4	66.7	0.29	61.5	ND
Typic Chromustert, Hungund series, Dharwar, Karnataka							
AP (0-9 cm)	8.7	26.7	38.1	35.2	0.62	ND	0.22
A 12(9-28)	8.7	23.2	17.8	59.0	0.66	57.2	0.22
A 13(28-44)	8.8	19.1	17.5	63.4	0.63	60.4	0.25
A 14(44-70)	8.9	18.1	16.8	65.1	0.64	60.0	0.16
A3Ca (70-81)	8.9	18.3	17.9	63.8	0.57	58.1	0.18
Cca (81-133)	ND	39.2	30.4	30.4	0.20	26.3	0.18
Typic Paleustalf Jamkhandi series, Bijapur, Karnataka							
AP (0-16 cm)	8.2	73.8	6.1	20.1	1.03	16.6	0.43
B1 (16-40)	8.5	65.1	5.8	29.1	1.17	23.8	0.14
B21t(40-61)	8.2	47.2	14.8	38.0	1.46	35.8	0.14
B22t (61-89)	8.3	44.0	10.5	45.5	1.15	38.4	0.13
B31 (89-123)	8.6	42.8	16.3	40.9	0.77	35.3	0.17
B32 (123-152)	8.5	51.9	8.9	39.2	0.51	29.8	ND
IIC (152-176)	8.2	59.7	9.8	30.5	0.22	23.9	ND

Source: Murthy et al 1982

cally for Indian conditions are again meager. A deep Vertisol (Typic Pellustert) at ICRISAT Center was found to contain 22-38 kg/ha nitrate-N in the upper 60 cm during late May before the rainy season. Nitrate-N level in the upper 120 cm soil was 37-64 kg/ha (Moraghan et al. 1983). It has been reported that the efficiency of soil N for sorghum may be independent of soil groups or genotypes (Ranganathan et al. 1974).

Widespread deficiency of Zn has been reported from soil analytical data. Other known micronutrient deficiencies concern Fe, Mn, and Cu. Such reports, however, represent only a beginning in our knowledge of micronutrient deficiencies. Details are discussed in section 4.6.

3.3 Fertilizer Use

The use of fertilizer in India is largely confined to irrigated areas and to commercial crops. In a survey of the 1968-71 period sorghum accounted for 3.5% of the total fertilizer used, giving an overall consumption figure of 4 kg/ha N + P₂O₅ + K₂O in the sorghum area (NCAER and FAI 1974). This and other surveys suggest that sorghum is comparatively better fertilized than pearl millet and

that fertilizer use is higher for the irrigated fields or those planted to HYCs (Jha et al. 1981; Jha and Sarin 1981). Interestingly, from the data the effect of moisture availability on fertilizer use at the field level is revealed, both directly and indirectly. In an all-India analysis, farmers preferred to use fertilizer on heavy soils rather than on light soils and the percentage area fertilized was positively correlated with rainfall (Jha et al. 1981). In a study of selected villages, irrigation and rainfall during the sorghum-growing months were the primary determinants for fertilizer use in Solapur (an area of undependable rainfall) but not in Akola (an area of dependable rainfall). At Akola, in none of the equations tested did rainfall appear as a significant variable (Jha and Sarin 1981).

It is still not possible to be precise about the magnitude of fertilizer use on sorghum. But it is known that it is very small considering the size of the crop's cultivation area, its low yield, and the concentration of fertilizer use in irrigated crops. In the top eight sorghum-growing districts mentioned in section 2.1, overall fertilizer use in 1978-80 varied from 5.5 to 22.7 kg/ha N + P₂O₅ + K₂O. In some of these districts sugarcane is an important crop, the growing of which affects the pattern of fertilizer

Table 3. Summary of the nutrient status of soils in 158 sorghum-growing districts of India.¹

Rating for available nutrient ²	Nitrogen		Phosphorus		Potassium	
	(no.)	(%)	(no.)	(%)	(no.)	(%)
Low	121	77	74	47	17	11
Medium	37	23	81	51	59	37
High	0	0	3	2	82	52
Total districts	158	100	158	100	158	100

Data source: IARI 1980b.

1. Districts with approximately 10,000 ha or more under sorghum.

2. General rating, not specifically for sorghum. The general criteria for low, medium and high are as tabulated below

Nutrient	Method	Low	Medium	High
N	Organic carbon	Below 0.5%	0.5-0.75%	Above 0.75%
N (kg/ha)	Alkaline permanganate	Below 280	280-560	Above 560
P (kg/ha)	Olsen's method	Below 10	10-24.6	Above 24.6
K(kg/ha)	Ammonium acetate	Below 108	108-280	Above 280

use. Some modal classes for fertilizer use on HYC sorghum derived from a survey conducted in 1973-74 are given in Table 4.

Indirect estimates also show that, assuming 80% of all-India fertilizer consumption is used on four crops-

Table 4. Modal classes for fertilizer use on HYC sorghum (nonirrigated) in 1973-74¹.

Nutrient	HYC area fertilized (%)	Nutrients applied (kg/fertilized ha) (N + P ₂ O ₅ + K ₂ O)
N	>60	21-40
P ₂ O ₅	<40	21-30
K ₂ O	<40	11-20

Source: Jha et al. 1981

¹ In 1973-74 approximately 7% of the sorghum area was under HYCs.

rice, wheat, sugarcane, and cotton (NCAER 1978; Sohbt 1979)—the remaining 20% amounts to an overall 13 kg/ha N + P₂O₅ + K₂O in the remaining 100+ million ha under all other crops, including well-fertilized plantations and other cash crops².

Although general indications are that sorghum does not receive much fertilizer, some systematic efforts in technology transfer have led to the use of fertilizers, an increase in crop yields, and higher net returns from sorghum cultivation (Aswathaiah and Krishna 1975; Chandrasekhar 1979; Sanghi and Rao 1982). Several surveys in this area are in progress at AICRPDA, IASRI, ICRISAT, and other centers.

2. Taking 1982-83 fertilizer consumption as 6.5 million tonnes of N + P₂O₅ + K₂O.

4. RAINY-SEASON SORGHUM

4.1 Aspects of Overall Importance

This section is considered to be of overall significance to sorghum research but is included here because most of the results on which it is based have been obtained either in the rainy season, under irrigated or under controlled conditions.

4.1.1 Genotype x Nutrient Interactions³

Considerable genetic variability in the chemical composition among 30 sorghum genotypes has been reported (Rao et al. 1979). Varietal differences for the tissue concentration of N, P, and K were found highly significant in studies which reported that the gene action was additive for N uptake but nonadditive for P uptake in sorghum hybrids. For nitrogen, % N in the leaf as well as its total uptake were positively and significantly correlated with yield but, for P and K, only their total uptake was correlated with grain yield. The coefficients of correlation (r) of the percentage of nutrient in the leaf at 40 days on grain yields were 0.64** (N), -0.52** (P) and 0.21 (K) (where ** = Probability level $P < 0.01$). The r values for total nutrient uptake with grain yield were 0.87** (N), 0.89** (P), and 0.88** (K). To produce high yields from hybrids, high leaf N + high uptake seemed to be the suggested requirement for N, while lower tissue concentration but high total uptake was preferred for P (Ramachandram and Rao 1974). The higher N concentration, as well as a higher demand for N by hybrids, may partially explain the greater susceptibility of these to charcoal rot and lodging.

Fourteen out of 21 sorghum hybrids were found to be heterotic for nitrate reductase (NR) activity and the nature of gene-action for NR was essentially nonadditive. The NR activity at flowering was positively correlated with yield, and it was suggested that the use of a high-NR parent could possibly ensure an above-average NR activity in the F1 hybrids (Mishra et al. 1981).

In rainfed trials with six cultivars at six locations over 3 years, it was concluded that "it is a false notion that performance of high-yielding hybrids and varieties is satisfactory under high input and optimum management, the locals may be preferred under low input and poor management" (Rao et al. 1981a). Top-ranking genotypes maintained their relative yield rank under "low" (40-20-20 kg/ha N-P₂O₅-K₂O, with no plant pro-

tection) as well as under "high" (80-40-40, with full plant protection) inputs and levels of management as classified by Rao et al. (1981a). It may be advantageous to select cultivars under two levels (optimal and sub-optimal). This is also borne out by data from the large number of experiments on farmers' fields (Kanwar et al. 1973; Mahapatra et al. 1973a). However, the needs of truly harsh environments must be taken into account in order to develop readily-transferable technology.

An interesting comparison between heterotic (CSH1, CSH 2) and nonheterotic hybrids (MsCK 60 x Aispuri; MsCK 60 x B.P. 53) showed that comparative transfer of absorbed nutrients to the ear was greater in the heterotic hybrids (Rao and Venkateswarlu 1971). Their conclusion that there seemed to be greater restriction on the movement of nutrients to the ear in nonheterotic hybrids is not clear because, in absolute terms, both types of hybrids produced ears of similar weight, which also contained similar amounts of nutrients (Table 5). It is likely that greater accumulation of nutrients in the stem of the nonheterotic hybrid was simply due to its massive stem, which weighed 3.34 times more than the stem of a CSH 1 plant, while ear weights for both types of hybrids were not greatly different. In other words, the nonheterotic hybrid produced much bigger plants but had a particularly unfavorable harvest index or source: sink relationship for grain production, which led to a less efficient use of nutrients it absorbed (Table 5). Genotypes with a higher harvest index will also have a correspondingly higher percentage accumulation of nutrients, such as N and P in the grain (ICRISAT 1981).

With respect to the rate of nutrient uptake between two heterotic hybrids, CSH 2 exceeded its superior parent for N while CSH 1 exceeded its superior parent for P, the latter also being characterized by a relatively heavier root system (Rao and Venkateswarlu 1971). A possible conclusion that CSH 2 may be more responsive to N than CSH 1 is, however, not borne out by a large number of field experiments on the N-responsiveness of these hybrids (Singh et al. 1981). Some preliminary indications of genotypic differences for response to K are available (Zende 1978b).

From bioenergetic considerations of photosynthate and nutrient-use efficiency, breeding for higher grain yield and a higher harvest index is considered to be a sound approach (Bhatia et al. 1981). The advantages of breeding for a higher harvest index will also be reflected in higher efficiency of the applied nutrients for grain production.

Laboratory studies show that, while hybrid CSH 8 exhibited heterosis in the absorption of Rb, hybrids CSH

3. Results for N, P, and K are reviewed here. Data on micronutrients, particularly on Zn, are presented in section 4.6.1, and on Fe in section 4.6.2.

Table 5. Differential accumulation of nutrients by a heterotic and a nonheterotic sorghum hybrid in relation to dry matter of different plant parts.

Parameter	Plant part	Heterotic hybrid CSH 1		Nonheterotic hybrid MsCK 60 x Aispuri	
		(g/plant)	(% of total)	(g/plant)	(% of total)
Nitrogen uptake	Ear	1.65	60.5	1.66	46.9
	Leaves	0.60	22.0	0.69	19.5
	Stem	0.48	17.5	1.19	33.6
	Total	2.73	100	3.54	100
P2O5 uptake	Ear	0.30	70.2	0.30	53.4
	Leaves	0.06	14.2	0.07	12.6
	Stem	0.07	15.6	0.19	34.0
	Total	0.43	100	0.56	100
K2O uptake	Ear	0.89	41.7	0.83	25.1
	Leaves	0.41	19.5	0.54	16.4
	Stem	0.82	38.7	1.94	58.5
	Total	2.12	100	3.31	100
Dry weight	Ear	93.6	41.5	92.8	21.8
	Leaves	31.6	14.0	43.7	10.3
	Stem	75.3	33.4	251.8	59.1
	Roots	25.0	11.1	37.7	8.8
	Total	226	100	426	100

Source: Rao and Venkateswarlu 1971

5 and CSH 6 were heterotic for the translocation of absorbed Rb to the shoots (Nirale et al. 1982). These workers suggested that several ion-uptake parameters should be examined when heterosis in hybrids is being studied.

4.1.2 Soil-test and Crop-response Correlations

Not much work has been done on soil-test crop-response correlations for rainfed sorghum. Even the suitability of the KMnO₄-oxidizable N as an index of available N for rainfed sorghum is questionable. The value of measuring nitrate-N in the soil profile for understanding the N-supplying capacity of soils is gaining acceptance (Rego et al. 1982). It is much more important for the postrainy-season sorghum that is grown after a long summer or rainy season. A method has been developed that includes NO₃-N in the estimate of available N for upland soils, but the field-testing and crop-response correlations have still to be worked out (Sahrawat and Burford 1982). It is possible that, in order to understand the dynamics of available N in soils, it would be better to recommend soil-testing for N rather than merely to recommend fertilizer doses. The success rate for an N soil test, however, is probably less than that of a P soil test.

For irrigated sorghum, commonly used methods—alkaline-permanganate oxidizable-N, sodium-bicarbonate extractable P (Olsen's method), and ammonium acetate-extractable K—have been reported to be suitable (Balasundaram et al. 1972; Balasundaram and Sree Ramulu 1980a; Bangar et al. 1979; Mehta and Singh 1971).

In the shallow red soils (Typic Ustorthents) of Bhavani-sagar, multiple regression between sorghum CSH 5 yield on available N, P, and K gave R² of 0.93 that was statistically significant at the 1% level of probability (Balasundaram and Sree Ramulu 1980a). But, when optimum doses for N and P were calculated from adjustment equations based on differentiation of partial regression equations, the results defied explanation. For instance, when available P varied from 5 to 17 kg/ha P, the optimum dose remained virtually the same at 19.3 and 19.0 kg/ha P respectively (Balasundaram and Sree Ramulu 1980b). It seems imperative that, if available nutrients in the soil are to be quantified and equated with the available nutrient pool, then chemical measurements must be integrated over the soil profile rather than be derived from the surface soil alone.

Some work on soil-test and crop-response correlations relating to the targeted yield approach has been carried out on hybrid sorghum under irrigation (Sonar et

al. 1982). These workers have also described a detailed procedure for calculating the nutrient requirements, contribution of soil nutrients, and of added nutrients, all of which are key components of this approach. A summary of results obtained in field verification trials in Vertisols is given in Table 6. The results indicate that, for the 3 t/ha and 4 t/ha targets, the fertilizer doses were being overestimated or, alternatively, that yield responses obtained were larger than those predicted. This approach is soil- and cultivar-specific, and also suffers from the overestimation or underestimation of the nutrient requirements. If the crop's nutrient requirement is overestimated or underestimated because of stress or other factors, it affects the computation of fertilizer doses. The P and K doses in relation to yields obtained (Table 6) also differ from many data discussed below that suggest there is a more widespread deficiency of P than that of K in sorghum-growing soils. Data for nonirrigated conditions are not available.

4.1.3 Sorghum-based Cropping Systems

Research on the soil fertility of sorghum-based cropping systems has so far been meager, although suitable crop combinations have been identified for different soil-climate areas (Randhawa and Venkateswarlu 1980; Spratt and Chowdhury 1978). Intercropping of sorghum with legumes, or sequential cropping, are common approaches for optimizing production by making the best use of soil, rainfall, and other climatic factors.

4.1.3.1 Intercropping. Intercropping rainfed sorghum is one means of increasing cropping intensity

(Randhawa and Venkateswarlu 1980; Venkateswarlu et al. 1981). In areas with "adequate" rainfall (1000 mm/yr) such as Indore, where the choice of cropping system is determined primarily by soil depth, moisture-storage capacities of 10 cm, 15 cm, and 20 cm were considered suitable for the intercropping and sole and sequential cropping of sorghum (Singh et al. 1981a).

While intercropping itself has been traditionally practiced and found advantageous in comparison with sole-cropping, researchers have examined this practice recently to determine the advantages in terms of the production stability associated with sorghum-based systems along with other advantages such as risk reduction, protein production, and the higher monetary value of the pulse/oil intercrops in the SAT (Freyman and Venkateswarlu 1977; Rao et al. 1981b; Rao and Willey 1981).

In most reports nutrient requirements and yields of intercropped sorghum are comparable with those of sole sorghum when the legume intercrop is added to full sorghum populations, especially at low to medium levels of N (Dusad and Morey 1979; Freyman and Venkateswarlu 1977; ICRISAT 1980; Reddi et al. 1980; Rego 1981). These data are illustrated in Figure 4. In some experiments, yields and grain response ratios to N of intercropped sorghum were slightly lower than those of the sole crop but the land-equivalent ratio (LER) was higher. The LER, which is a measurement of the efficiency of land use, was high under intercropping, the total LER being 1.68, 1.39, and 1.47 at 0, 60, and 120 kg/ha N respectively (Rego et al. 1982). Higher yields of sorghum intercropped with legumes (except soybean) in comparison with sole sorghum have also been reported (IAR11980a). In a sorghum/pigeonpea system

Table 6. Some results of field verification trials of fertilizer doses calculated for different grain-yield targets of sorghum: irrigated CSH 5 on Vertisols in Maharashtra.

Trial no. and year	Target: 3t/ha		Target: 4 t/ha		Target: 5 t/ha	
	Fertilizer applied (kg/ha)	Yield obtained (t/ha)	Fertilizer applied (kg/ha)	Yield obtained (t/ha)	Fertilizer applied (kg/ha)	Yield obtained (t/ha)
	N-P2O5-K2O		N-P2O5-K2O		N-P2O5-K2O	
1 (1980)	80-0-34	3.40	Not tested	ND	164-29-110	4.90
2(1980)	82-0-0	3.80	Not tested	ND	163-29-0	4.70
3(1981)	86-0-4	3.59	126-0-43	4.29	167-0-81	5.46
4(1981)	67-0-89	2.99	107-0-128	5.33	147-0-166	5.81
5(1981)	60-0-66	4.30	100-0-104	4.64	140-0-143	5.35
6(1981)	0-0-29	3.57	27-0-67	4.11	67-0-105	4.60
Mean		3.61		4.59		5.14

Source: M. Velayutham, All India Coordinated Soil Test Crop Response Correlation Project, personal communication 1982. For details of procedures used in calculating the above doses, and a summary of follow-up trials, see Sonar et al. 1982.

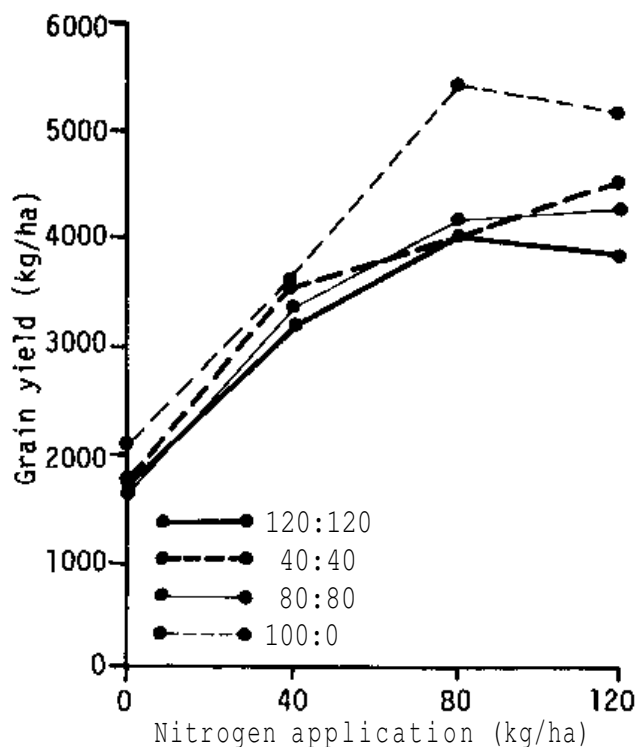


Figure 4. Nitrogen response of sole sorghum and different populations of sorghum intercropped with pigeonpea on Vertisols at ICRISAT, 1977. (Rego 1981.)

pigeonpea did not seem to contribute any N to the companion crop of sorghum (Rego 1981).

In two Alfisol sites intercropped sorghum gave 95% of the sole-crop yield, and an additional 0.4-0.5 t/ha of pigeonpea or green gram could be harvested (Reddi et al. 1980). Under irrigated conditions, sorghum Co.21

gave similar yields when grown as a sole crop and fertilized with 75-30-30 kg/ha of N-P₂O₅-K₂O or when intercropped with green gram/chickpea/cowpea and fertilized with 45-30-30 (Morachan et al. 1977).

While the stimulation of dwarf sorghum's growth by N may not always result in excessive competition for light, water or nutrients with pigeonpea (ICRISAT 1978), tall sorghums can smother pigeonpea and reduce its yield (Narain et al. 1980). In a study of intercropped long-duration sorghum/pigeonpea conducted at Kota (on a Vertisol), intercropped pigeonpea was estimated to add 10-40 kg/ha N to the soil through leaf litter.

In the 3-year study under rainfed conditions at Kota, year-to-year variation in sorghum yields was greatest in the unfertilized plots (Figure 5), although significant response was obtained only to N application (Narain et al. 1980).

4.1.3.2 Sequence cropping. Double cropping of sorghum under rainfed conditions has been demonstrated to be feasible in a deep Vertisol (Rego et al. 1982). Even when there was adequate moisture in the soil profile after the harvest of the rainy-season crop, yield of post-rainy-season sorghum was less than 0.5 t/ha (attributed to nitrogen stress). Application of 40 kg/ha N resulted in a second-crop grain yield of 1.8 t/ha, thus indicating the importance of N application in utilizing the moisture stored in these soils (Table 7). Lower grain yields in the post-rainy season, after a rainy-season crop, could also have been due to there being less water in the profile for the post-rainy season crop as compared with the rainy-season fallow. There is also an indication that deep-rooted cultivars may be utilizing more nitrate from the lower soil layers, and may thus show lower response to applied N.

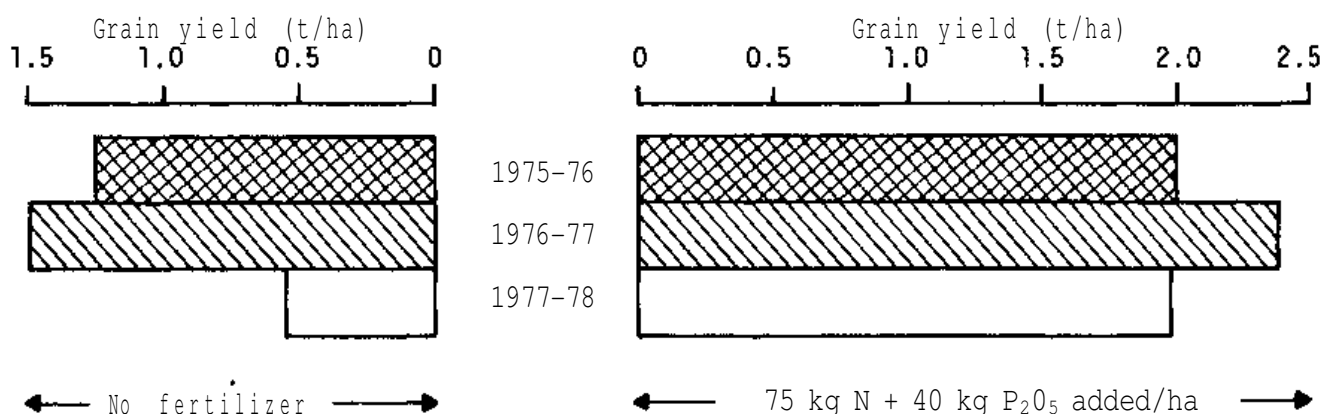


Figure 5. Yield fluctuation in fertilized and unfertilized rainfed sorghum. (Narain et al. 1980.)

Table 7. Effect of cropping system in the rainy season on the response of post rainy-season sorghum to 40 kg/ha N on a Vertisol.

System in rainy season	Grain yield of the postrainy-season sorghum (t/ha)	
	Zero N	40 kg/ha N
Fallow	1.48	2.87
Sorghum	0.43	1.84

Source: Rego et al 1982.

4.1.4 Nutrients and Root Growth

Both genetic and environmental factors affect the growth and distribution of sorghum roots. In ³²P-studies, differences in rooting patterns between genotypes were highly significant at the knee-high stage. In most dwarfs, at 5-cm lateral distance, root activity was concentrated in the top 10 cm of soil but spread out with depth. Cultivar 302 (CSV 2) was observed to be more tolerant of drought than CSH 1 and Swarna (CSV 1) and the root activities correlated with yields in all-India trials in seasons of normal and deficit rainfall (Damodar et al. 1978).

In comparisons between CSH 1 and Swarna (CSV 1), the root system of CSH 1 has been described as more efficient because it had a greater number of deeper roots at later stages, and the proportion of its roots below 15 cm increased with increasing rate of N application. Hybrid CSH 1 produced more grain per unit root weight as compared with Swarna (Panchal et al. 1972). In plots receiving N, roots continued to grow after flowering whereas root growth had ceased in unfertilized plots (Warsi and Wright 1973c).

In a 2-year study with CSH 1 on a clay soil under faired conditions, depth, spread, and the mass of roots were maximal with 120 kg/ha N + 50 kg/ha P₂O₅ (Khybri and Singhal 1976). These data suggest that while N affected both the vertical and lateral spread of the roots, the effect of P was comparatively more on the lateral spread.

The cation-exchange capacity (CEC) of the roots of 12 sorghum cultivars has been found to vary from 11 to 22 me/100 g dry weight and, in most genotypes, increased up to 60 days after seeding. The CEC of the roots of HYCs was more than that of the traditional cultivars. Correlation of root CEC with N content of plants was significant at all stages of growth, but *r* values changed from +0.65** in 60-day-old plants to -0.50** at harvest (Chhabda et al. 1978). Correlations of P, K, Ca, and Mg in plants with CEC of the roots were generally higher at 60 days than at any other growth stage (Chhabda et al. 1979).

4.1.5 Nutrient Removal in Sorghum Production

A detailed discussion of this aspect is provided in sections 4.2 to 4.6, but an example of the nutrients removed by hybrid sorghum under rainfed conditions is provided in Table 8 (Vijayalakshmi 1979).

Table 8. Removal of nine nutrients by rainfed hybrid sorghum.

Nutrient	Grain (t/ha)	Total uptake by grain+ stover
N	4.4	78 kg
P ₂ O ₅	4.4	35 kg
K ₂ O	4.4	117 kg
Ca	2.6	29 kg
Mg	2.6	17 kg
Fe	4.4	705 g
Mn	4.4	447 g
Zn	4.4	132 g
Cu	4.4	37 g

Sources :Ca and Mg data are for CSH 1 in a Vertisol (Lakhdive and Gore 1978)
All other data are for CSH 5 in an Alfisol (Vijayalakshmi 1979).

4.1.6 Grain Quality and Nutrients

In a survey of 332 sorghum entries, 70-80% samples had 10-14% protein in the grain. Lysine formed 1.5-2.5% and leucine 9-13% of the protein (Mohan 1968). In another survey 60 out of 96 genotypes were found to contain 12% or more protein in the grain (Austin et al. 1972). Results from screening 6758 sorghum samples for grain quality gave a mean protein content of 12.1% (range 6.0 to 21.1 %) and a lysine estimate of 3.01 % of the protein in the range of 1.84 to 5.57% (ICRISAT 1977). A frequency distribution of some quality characteristics of sorghum grain is given in Table 9.

Environmental factors affected protein and lysine content but not leucine (Mohan 1968). Karad in Maharashtra state has been identified as a location where all cultivars recorded lowest grain protein contents (4.9 to 6.5%: Deosthale and Mohan 1970). Causes for low protein have not been explained.

Nitrogen application increases N uptake and therefore the protein content in grain (Deosthale et al. 1972; Gupta and Gupta 1972). Factors that reduce N uptake, such as weed competition, also reduce grain protein (Sankaran and Mani 1975). The effect of N is generally to increase protein in the grain from 9-10% to 12-13% (Roy and Wright 1973b; Singh and Bains 1973; Warsi and Wright 1973d).

As N application increases the protein and prolamine fractions, the increase in the quantity of protein may not

Table 9. Frequency distribution for protein, lysine, and leucine contents in sorghum grains.

Range	No. of samples	% of total samples
Protein was determined in 10 479 samples with the Technicon auto-analyser.		
PROTEIN (%)		
Below 6	71	0.7
6.01- 8.00	613	5.9
8.01-10.00	2334	22.3
10.01-12.00	3557	33.9
12.01-14.00	2542	24.3
14.01-16.00	1097	10.5
Above 16.00	265	2.5
Lysine was estimated in 10 426 samples with the rapid dye binding capacity method		
LYSINE (g/16g N)		
Below 1.50	54	0.5
1.51-2.00	4239	40.7
2.01-2.50	4836	46.4
2.51-3.00	975	9.4
3.01-3.50	242	2.3
Above 3.50	80	0.8
Lysine was determined in 64 samples with the amino acid analyser		
LEUCINE (g/16g N)		
Below 9.00	6	9.4
9.00-12.00	25	39.1
12.01-15.00	22	34.4
Above 15.00	11	17.2

Source: R Jambunathan, ICRISAT, personal communication 1982.

be accompanied by an improvement in the quality of protein (Gupta and Gupta 1972). This is primarily because an increase in prolamine is responsible for the amino-acid imbalance and is generally accompanied by a decrease in lysine content (lysine being the most limiting essential amino acid). Often the protein and lysine contents are negatively correlated (Austin et al. 1972; Deosthale and Mohan 1970; Mohan 1968; Swaminathan et al. 1971; Tripathi et al. 1971; Warsi and Wright 1973d). After lysine, the most limiting amino acids are stated to be methionine, cystine, and threonine (Jambunathan et al. 1984).

High-yielding variety Swarna (CSV 1) is considered to be nutritionally superior to hybrids CSH 1 and CSH 2 on the basis of protein and lysine contents (Deosthale and Mohan 1970; Gupta and Gupta 1972).

In some yellow-endosperm sorghums, soil application of 56 kg/ha N increased the β -carotene in grain by 30-50% (Kapoor and Naik 1970).

On a P-responsive soil the application of P increased grain yields and N uptake but had no effect on the percentage of protein in the grain of CSH 1 (Roy and Wright 1973b).

4.1.7 Microbiological Factors in Sorghum Nutrition

4.1.7.1 Azotobacter. Reports on the effect of azotobacter on sorghum yields vary from no effect (Rao and Das 1982; Srivastava et al. 1975), to "phenomenal increases" (Shende 1982). In Alfisols at Hyderabad, inoculation with azotobacter increased grain yield of CSH 5 by 200 kg/ha in one year and by 470 kg/ha in another (Reddy et al. 1977).

4.1.7.2 Azospirillum. Some significant yield responses to azospirillum have been reported (Rao 1979), while unpublished reports from the AICSIIP show that, as an average over six locations with CSH 5 hybrid, yield gains due to azospirillum in 1980-81 with or without fertilizer N were less than 100 kg/ha. In a 2-year study with CSH 5 at Pantnagar, the effect of *Azospirillum brasiliense* was generally more consistent on N uptake than on grain yields (Pal and Malik 1981). The magnitude and trend of results are shown in Table 10. Differ-

Table 10. Effect of *Azospirillum* inoculation on the grain yield and N-uptake by sorghum hybrid CSH 5 (kg/ha).

N-P-K treatment (kg/ha) and inoculation	1978		1979	
	Grain yield	Nitrogen uptake	Grain yield	Nitrogen uptake
0-26-33(U)	1170	63.5	2430	95.2
0-26-33(I)	1780	78.2	2820	101.6
40-26-33(U)			3250	102.5
40-26-33(I)			3085	107.8
0-26-33 plus FYM, 10t/ha(U)	2050	66.5	2756	98.9
0-26-33 plus FYM, 10 t/ha (I)	2440	83.0	2622	104.6
SE	±219	±2.04	±228	±1.56
CV (%)	16.7	11.5	13.6	6.7
Remarks	Unfavorable rainfall distribution, poor grain setting H.I. 20%.		Profuse grain setting H.I. 30%.	

Source: Pal and Malik 1981. U = uninoculated; I = inoculated.

* In 1978 the data for 40-26-33 were highly variable and have not been considered as in the uninoculated plots; 40 kg/ha N top-dressed gave 1.2 t/ha extra grain over 40 kg N basal, but in the inoculated plots difference between the two methods of N application was less than 0.1 t/ha.

ences in grain yield were not consistent. Studies are continuing to exploit this potential.

4.1.7.3 Phosphobacterin. In a preliminary field trial, seed inoculation with phosphobacterin was reported to increase the P uptake of a rainfed crop of sorghum Co. 20 from 2.1 to 3.6 kg/ha P (Rangaswami and Morachan 1974).

4.1.7.4 Mycorrhiza. In a pot study with CSH 5 hybrid, mycorrhizal inoculation increased plant weight and P uptake, both in the absence and presence of applied P. In an Alfisol with 6 ppm available P, the plant growth increased with the application of P which was further improved with mycorrhizal inoculation (Krishna and Bagyaraj 1981). Studies are continuing.

4.1.8 Weed Competition for Nutrients

Reports of field studies with hybrid CSH 1 indicated that, on average, every 10 kg of nutrients (4.5 N + 1.5 P₂O₅ + 4.0 K₂O) removed by weeds brought about a 100 kg reduction in sorghum grain yield (Sankaran and Mani 1972). Removal of nutrients by weeds varied from 112 to 162 kg/ha of N + P₂O₅ + K₂O in the first 35 days after sowing which exceeded the nutrient removal in sorghum by a factor of 2 to 4 for N or P and 1 to 2.5 for K. These experiments indicate that more than one cycle of weed growth occurs during sorghum's life-span. A quantitative assessment of total nutrients removed and immobilized by the weed biomass was therefore not possible from sampling undertaken close to sorghum harvest-time. The yields of sorghum dry-matter, grain, protein, and the nutrient uptake, all showed significant negative correlations with their corresponding parameters in weeds (Sankaran and Mani 1975).

4.1.9 Other Topics

4.1.9.1 Salt-tolerance. Salinity can be a factor in the management of Vertisols (Finck and Venkateswarlu 1982; Murthy et al. 1974).

Significant differences among sorghum cultivars in their tolerance of salinity have been reported with highly tolerant types recording 80% germination at 16 mmho/cm E.C. (Abichandani and Bhatt 1965). In general, sorghum is sensitive both to salinity and to sodicity (Maliwal 1967; Murthy et al. 1974; Paliwal and Maliwal 1980). Among anions, bicarbonate was rated as most toxic and sulphate the least toxic in germination tests made with synthetic salt solutions (Paliwal and Gandhi 1968). Hybrid CSH 1 has been rated as more tolerant than CSH 2 to salt (Patel and Dastane 1968).

Potassium content of 30-day plants has been proposed as an index for tolerance of salt by sorghum cultivars. Based on tests with 20 cultivars, K content of 0.7-0.9% seemed to indicate tolerance of salt, and less than 0.4% K indicated susceptibility. For instance, cultivar Co.4 had 0.9% K and it was found to be tolerant of 5000 ppm salinity (Pathmanabhan and Rao 1976).

4.1.9.2 Sorghum nutrition and HCN. Under similar conditions, HCN in hybrid CSH 1 was higher than in the local cultivar M-35-1 and maximum concentration was observed in 10-day old plants, after which it declined. The HCN content increased with the rate of N application but decreased when both N and P were applied (Shaikh and Zende 1971 a). The effect of different sources of P on HCN content was of the same order as their contribution to the plants' uptake of P (Shaikh and Zende 1970). In 35-day old plants of cultivar J.S.263, least HCN content of about 500 ppm on a dry-matter basis was observed when N and P₂O₅ were applied in a 2:1 ratio (Verma and Abrol 1971).

4.2 Nitrogen

The most widely investigated aspect of sorghum research in India seems to be the "response of hybrid CSH 1 to increasing rates of N application." In the following subsections, therefore, nitrogen research on rainy-season sorghum is discussed.

4.2.1 Crop Growth and Nitrogen Accumulation

The N-accumulation curve is generally similar to the sigmoidal growth curve in sorghum. In the 1st month after seeding, 4-7% of the total dry-matter is produced (Kudasomannavar et al. 1980b; Lanjewar and Khot 1978; Roy and Wright 1973b; Singh and Bains 1973; Venkateswarlu et al. 1980; Warsi and Wright 1973a). The rate of N accumulation generally exceeds the rate of dry-matter production in the early stages. The two curves cross at about 60-65 days after sowing, and thereafter dry-matter accumulation proceeds at a somewhat faster rate than N absorption (Rao and Venkateswarlu 1971; Roy and Wright 1974; Warsi and Wright 1973b). This phenomenon, however, was not observed under the humid subtropical conditions at Pantnagar where the rate of N accumulation was continuously ahead of the rate of dry-matter production (Venkateswarlu et al. 1980). Illustrative data for two different situations are given in Table 11.

Unfertilized sorghum completes dry-matter production and N uptake earlier than a well-fertilized crop, but an unfertilized crop does not necessarily mature earlier than a fertilized crop. In the latter case, dry-matter

Table 11. Comparative rates of accumulation of dry-matter (DM) and nitrogen (N) in sorghum hybrid CSH 1 at two locations in the rainy season.

Days after sowing	N applied (kg/ha)	Accumulation (% of total)			
		Semi-arid (Delhi)		Subhumid (Pantnagar)	
		DM	N	DM	N
28 to 30	0	6	13	6	14
	120	5	9	7	13
60 to 63	0	72	75	60	63
	120	48	47	56	63
75 to 77	0	88	87	83	91
	120	69	65	78	90

Source; Roy and Wright 1973b, 1974; Venkateswarlu et al 1980

accumulation and nutrient uptake continue almost up to maturity (Kudasomannavar et al. 1980b; Lanjewar and Khot 1978; Roy and Wright 1973b, 1974; Warsi and Wright 1973a, 1973b) and this difference is much less in soils of the humid subtropics containing high organic matter (Venkateswarlu et al. 1980).

In an alluvial soil (Typic Haplustalfs) deficient in N and P, recoveries of N and P in the heads were lower unless both the nutrients were applied (Roy and Wright 1974). The importance of balanced nutrition was reflected in higher yields, a higher harvest index, and a greater diversion of the absorbed nutrients towards the grain (Table 12). In two treatments with similar total accumulation of N (112-115 kg/ha N), the heads contained 72% of accumulated N in the NP plots but 62% of accumulated N in the N-only plots.

4.2.2 Yield Response to Nitrogen Application

A recent summary of the response of sorghum genotypes in the rainy season based on the findings of the

Table 12. Role of nitrogen and phosphorus application on absorbed nutrients diverted for grain production in sorghum hybrid CSH 1 in the rainy season.

Plant part and yield	Effect of P on N ($N_{120}P_{26} - N_{120}$)	Effect of N on P ($N_{120}P_{26} - P_{26}$)
Stem	+ 2.4 kg N	+ 0.4 kg P
Leaves	- 1.8 kg N	+ 0.5 kg P
Head	+36.1 kg N	+10.9 kg P
Total	+368 kg N	+12.0 kg P
Grain yield	+ 1.83 t/ha	+ 2.05 t/ha

Source Roy and Wright 1974

AICSIP is given in Table 13 (Pal and Singh 1970; Pal et al. 1982; Singh et al. 1981b). It is assumed, in these experiments, that sorghum received protective irrigation (Kanwar 1978) and a basal dose of phosphates. The data provide an estimate of a HYC's (generally hybrids) mean performance in all-India trials, and the superiority of HYCs over traditional cultivars at all levels of N. The response ratio at the optimum level of N (130-140 kg/ha N) is about 10-12 kg grain per kg N applied.

Since sorghum is raised predominantly as a rainfed crop, responses of sorghum to N under rainfed conditions in different soils are presented in Table 14. These data have been averaged from several papers for a location and, in all studies on N, an "optimum" application of P and, where necessary, of K, was also given. Optimum rates of N for rainfed HYC sorghums in the rainy season are seen to vary from 60 to 120 kg/ha N and, at these levels, an overall response rate (grain yield increase over 0-N) of 18.3 kg grain/kg N is obtained (Table 14). At assumed prices of Rs5/kg N and Rs 1.2/kg sorghum grain, a response of 18.3 kg/kg N is equivalent to a value:cost ratio of 4.4. A response of 4.2 kg grain/kg N is required to pay for fertilizer N, and the balance is net profit.

Table 13. A summary of responses of sorghum HYCs to nitrogen application in the rainy season (from AICSIP trials).

Variety ¹ (trials)	Response function	R ²	Optimum dose (kg/ha N)	Response (kg/kg N) at optimum dose
CSH 1 (46)	$Y = 2018 + 21.66 X - 0.065 X^2$	0.996	140	12.5
CSH 2 (38)	$Y = 1880 + 16.48 X - 0.043 X^2$	0.996	152	9.9
CSH 3 (24)	$Y = 2064 + 22.39 X - 0.072 X^2$	0.996	132	12.9
CSH 4 (18)	$Y = 1818 + 17.48 X - 0.044 X^2$	0.999	160	10.4
CSV 1 (41)	$Y = 1686 + 16.98 X - 0.052 X^2$	0.992	131	10.2
Local (21)	$Y = 1376 + 3.14 X$	0.872	*	*

Source: Singh et al. 1981b

1. Hybrid CSH 4 is the same as PSH 2, and CSV1 is the same as Swarna

* As response function is linear, optimum dose cannot be calculated

Table 14. Responses of rainfed sorghum to optimum or near-optimum levels of nitrogen application in field experiments in India in the rainy season.

No.	Soil (trials averaged)	Location (cultivars)	Yield of zero N plots (t/ha)	N level (kg/ha)	Response*** (kg/grain/kg N)
1	Alfisol (8)	Hyderabad (Hybrids)*	1.35	80	21.6
2	Alfisol (3)	Vizianagaram (CSH 1)	2.67	100	21.9
3	Vertisol (2)	Hyderabad (CSH 6)	1.18	120	28.5
4	Vertisol (2)	Dharwar (CSH 1)	2.39	100	14.2
5	Vertisol (8)	Akola (CSH 1)	1.35	50-60	24.2
6	Vertisol (5)	Akola (CSH 1)	1.47	100-120	16.7
7	Vertisol (3)	Dhule(CSH 1)	2.97	100	12.7
8	Vertisol (2)	Kohlapur (CSH 1)	2.39	100	17.2
9	Vertisol (2)	Nagpur (CSH 1)	1.88	75	24.2
10	Vertisol (3)	Parbhani (CSH 5)	3.11	120	20.6
11	Vertisol (3)	Kota(CSH 1)	0.77	75	10.1
12	Vertisol (3)	Rajkot (CSH 1)	1.37	90	14.8
13	Ver.-Alf. (5)	Jhansi (MauT1,T2)	1.22	60-80	13.6
14	Mollisol (6)	Pantnagar (CSH I)	2.60	80-100	11.9
15	Entisol (6)	New Delhi (CSH I)**	2.66	60	24.3
16	Entisol (4)	New Delhi (CSH I)**	0.82	100	16.0

- * Hybrids CSH 1, CSH 5, CSH 6.
Protective irrigation when needed; Inceptisols/Entisols both occur
References for serial nos. 1-16 are as follows
- **1. Chowdhury and Chetty 1979. ICRISAT 1974; Reddi et al. 1980, Venkateswarlu and Rao 1978
2. Hussaini and Rao 1968a, 1968b; Pantulu et al. 1972.
3. Rego 1981.
4. Veeranna and Patil 1978
5. Bhendia et al. 1975; Dahatonde and Adhaoo 1978; Nagre 1981; Nagre and Bathkal 1979
6. Dahatonde and Adhaoo 1978; Nagre 1981; Nagre and Bathkal 1979
7. Patil and Surve 1980
8. Bathkal et al. 1970.
9. Choudhari and Mahalle 1970; Lanjewar and Khot 1978.
10. Bhalerao 1977; Bhalerao et al. 1977; Rogde and Tak 1975
11. Khybn and Singhal 1977.
12. Parmar 1979
13. Gahlot et al 1979; Mehrotra et al. 1979.
14. Lai et al. 1973; Singh et al, 1971; Venkateswarlu et al. 1977.
15. Roy and Wright 1973b, Shukla and Seth 1976; Singh and Bains 1972
16. Singh and Singh 1977, 1978.

A synthesis of 12 reports covering 24 experiments shows that the dominant factor contributing to higher grain yields is an increase in the number of grains per panicle as a result of fertilizer application. On average, N application increased grains per panicle by 61 %, which increase was also reflected in a 58% enhancement of panicle weight. Increase in grain weight was about 4% except in two reported experiments where N application increased the 1000-grain weight of sorghum hybrids and varieties by 10-16% (Singh and Singh 1977,1978). Another aspect emerging from many reports is that the fertilized crop flowered and matured 6-10 days earlier.

While we have provided above an overall averaged assessment of the response of sorghum to N, it should be noted that N response, with reference to soil-climate-management conditions, still eludes satisfactory interpretation. Some of the reasons for this have

been mentioned in section 1.4. A simple correlation between seasonal rainfall and yields also does not emerge, except in selected years, and in many cases yields are lower in years of high rainfall (Parmar 1979; Venkateswarlu et al. 1977; ICRISAT 1983).

To illustrate the complications of interpreting the N-response data and explaining it in terms of known variables, the results from 12 experiments conducted at IARI were examined. All were field experiments with hybrid CSH 1. They received from zero to three irrigations, depending upon the season's rainfall. It was found that yields and responses to N were anywhere within the two curves shown in Figure 6. Yields of the 0-N plots varied from 0.6 t/ha to 36 t/ha. Seasonal rainfall or organic matter content of the fields could not be directly related to grain yields or responses.

In addition to experiments on research stations, a

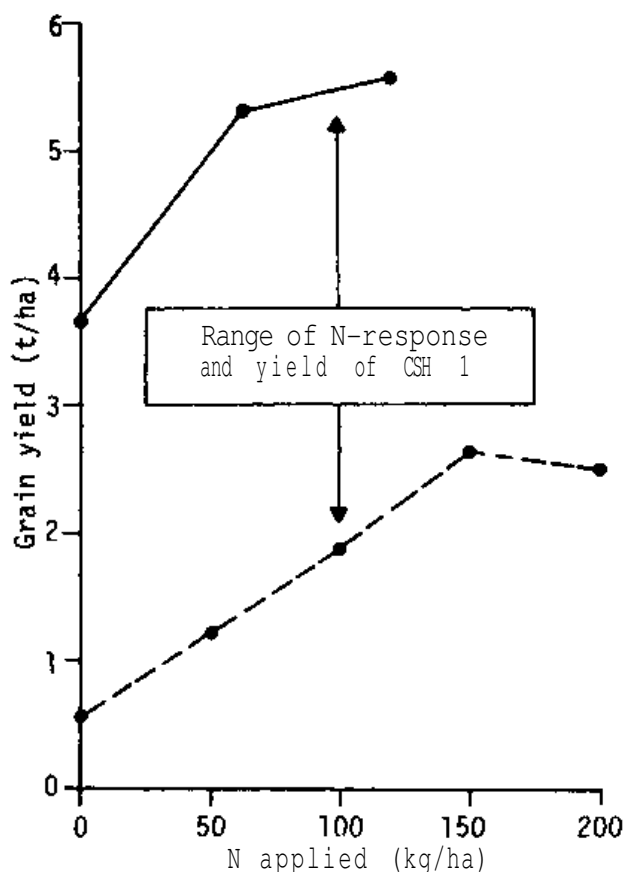


Figure 6. Upper and lower range of response to N and yield of the same hybrid at the same location as selected from 12 season's data with CSH 1 at New Delhi. (Upper curve Roy and Wright 1973b; lower curve Singh and Singh 1978.)

large number of fertilizer trials on farmers' fields have been conducted under the auspices of AICARP since 1967, initially with traditional cultivars and later with HYCs. These results have been periodically summarized (Kanwar et al. 1973; Krishnan 1978; Mahapatra et al. 1973a; Raheja et al. 1970; Randhawa and Tandon 1982; Sharma et al. 1973; Singh et al. 1976a). Fertilizer responses in terms of parameters of additional production have been computed and an overall summary is given in Figure 7 (Leelavathi and Bapat 1979). It may be observed that in most of the sorghum-growing states responses to P are higher than to N (Fig. 7), indicating that deficiency of P in sorghum-growing areas is severe.

Studies in Maharashtra indicate that sorghum yield and response to fertilizer was lower in shallow soils than in deeper soils (Sahasrabudhe 1972; Sharma et al. 1973). Clay loams of medium depth which ensured good drainage and an adequate water-holding capacity

were considered highly suitable for sorghum (Sahasrabudhe 1972). In the Bundelkhand region of Uttar Pradesh, sorghum performed better on loams than on clay loams (Tiwari and Singh 1972). In the Dharwar area moisture conservation practices, e.g., "putting a bund around the field and ploughing across the slope" added 100-250 kg/ha to the grain yield (Kulkarni et al. 1977).

Multilocation data on fertilizer responses have been compiled by AICRPDA. These should now be taken into account in formulating new parameters for sorghum production because they include additional information, available in the last 10 years, on the integration in the field of knowledge about fertilizer applications, water management, and optimum planting times that are important in assessing fertilizer responses.

4.2.3 Nitrogen Uptake and Recovery

Data from control (0-N) plots of several experiments show that 25-83 kg/ha N can be removed by sorghum from different soils (J.R. Burford, ICRISAT, personal communication 1982; Kumar and Awasthi 1977; Lanjewar and Khot 1977; Naphade and Chaudhary 1974; Patil et al. 1974; Roy and Wright 1974; Venkateswarlu et al. 1978). At assumed mineralization rates at 4-5% per year, soils in the semi-arid tropics can provide these quantities of N, but experimental evidence on mineralization rates is scarce (Dart and Wani 1982).

When soils are deficient in P, uptake of soil N can increase by 50% as a result of P application (Roy and Wright 1974). Cultivars producing large amounts of biomass remove greater quantities of soil N (Lanjewar and Khot 1977). Nutrient uptake for a cultivar is directly proportionate to the levels of production, as shown in Figure 8. A 5.5 t/ha grain crop removed a total of 335 kg/ha nutrients (149 N + 61 P₂O₅ + 125 K₂O).

As an overall average, HYC sorghums remove 22 kg/ha N to produce 1 t/ha of grain (Table 15). A rainfed crop of CSH 1, producing perhaps the highest reported grain yield of 8.6 t/ha, removed 205 kg/ha N under a fertilizer application rate of 200-75-40 kg/ha N + P₂O₅ + K₂O in a Vertisol at Dharwar (Kudasomannavar et al. 1980a). In this trial, top-dressed N was "banded 5 cm deep" 30 days after sowing.

There is little published information on the recovery by sorghum of added N from ¹⁵N-measurements under Indian conditions or on N-balance aspects of sorghum in drylands in general (Vlek et al. 1981). "Apparent" crop recoveries of N by the difference method can range from 55 to 105%, and are of limited value in precise quantitative terms (Kudasomannavar et al. 1980a; Lanjewar and Khot 1977; Naphade and Chaudhary 1974; Roy and Wright 1974; Venkateswarlu et al. 1978). Crop

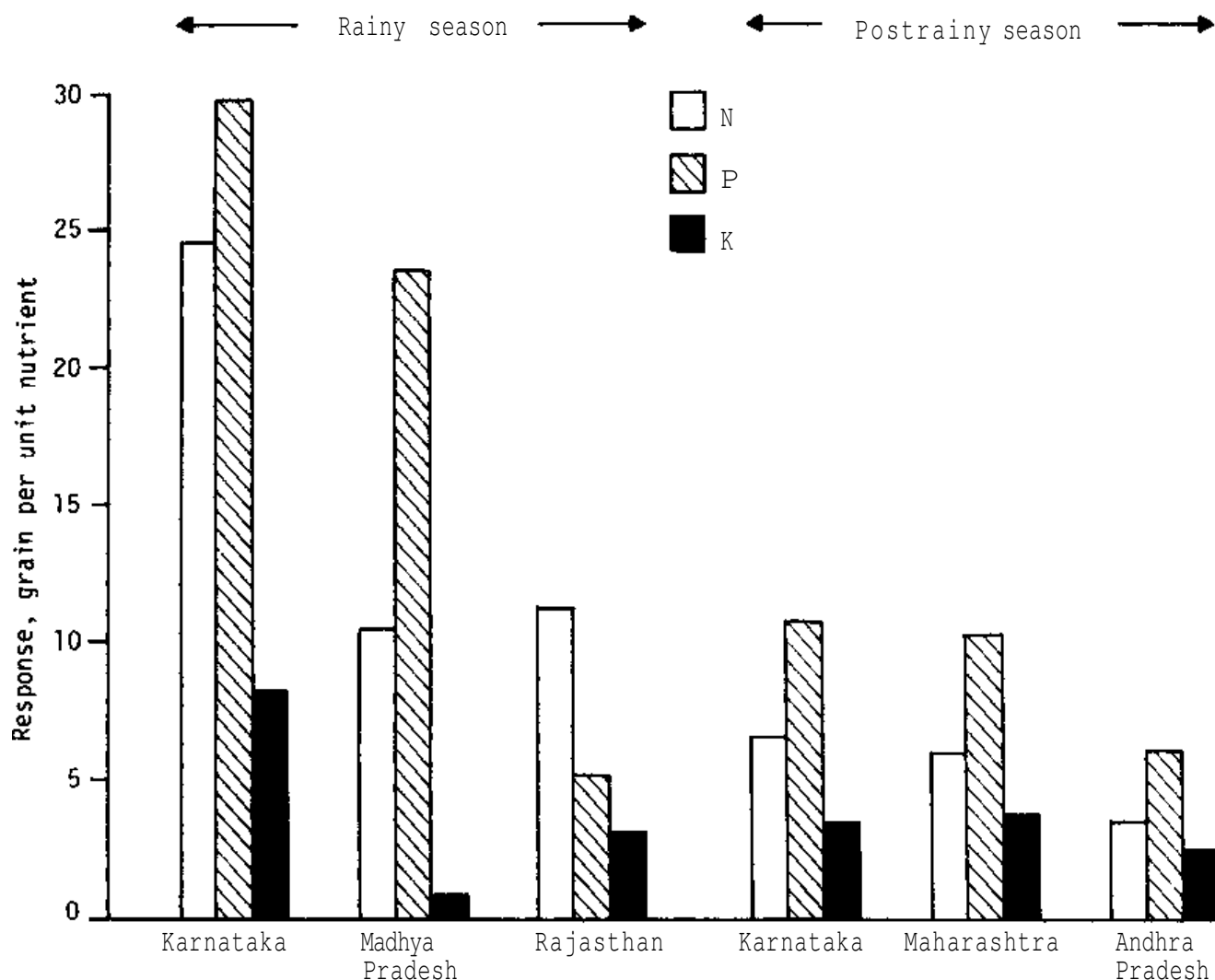


Figure 7. Parameters of additional production of sorghum from fertilizer use under conventional dry-farming conditions. (Leelavathi and Bapat 1979.)

recovery values of N increased with P application in a P-deficient soil from 36 to 55% (Roy and Wright 1974). "Apparent" recovery of N was markedly improved when N was applied in two or three splits in a high-rainfall year, as illustrated in Figure 9 (Venkateswarlu et al. 1978). This could be a combined effect of supplying N during periods of active crop growth, N absorption and presumably lower leaching losses. Some results with ^{15}N -labeled urea have now become available under field conditions for an Alfisol as well as a Vertisol (ICRISAT 1982; ICRISAT 1983; Moraghan et al. 1983). Across several levels and methods of N application the various aspects studied were: yield response; uptake

and crop recovery of added N; and distribution of added N in the soil profiles and its residual value to a succeeding crop.

At comparable levels (74-80 kg/ha N) and methods (band-split), the sorghum crop recovered 62.5% added N in the Alfisol and 55.0% in the Vertisol. At the end of the season, 27.1% fertilizer N was distributed in the Alfisol profile and 38.6% in the Vertisol profile. Thus a total of 89.6% and 93.6% N could be accounted for by the soil + crop system.

In the Alfisol, crop recovery of added N varied rather narrowly from 46.3 to 51.1 % as N levels increased from

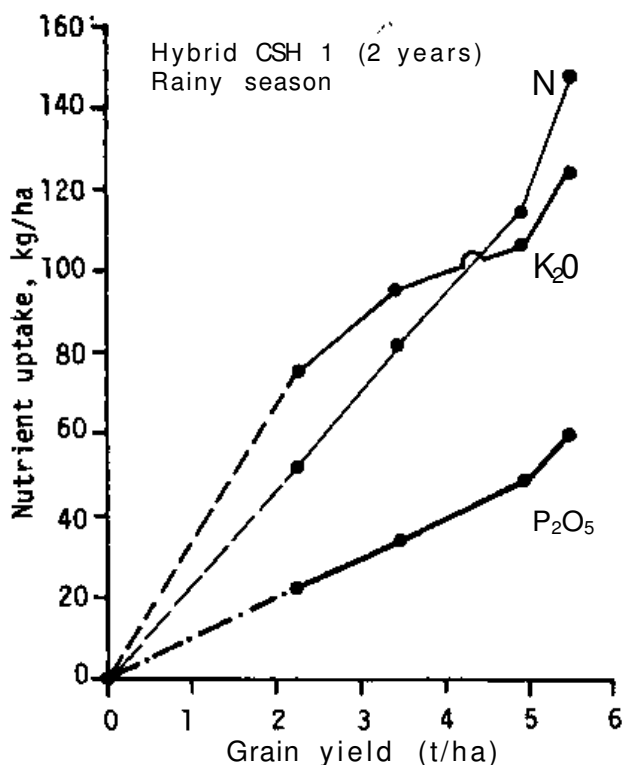


Figure 8. Yield of hybrid CSH 1 at increasing fertility levels and the associated removal of NPK. (Roy and Wright 1974.)

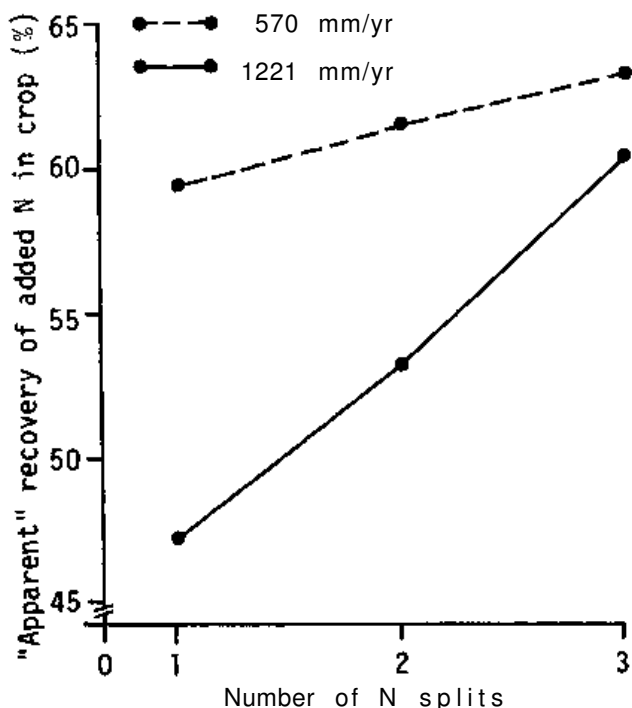


Figure 9. Nitrogen utilization by CSH 1 as affected by split application of N on a coarse loam in rainy seasons of different rainfall. (Venkateswarlu et al. 1978.)

Table 15. Removal of N, P, and K by sorghum hybrids in the rainy season under field conditions in India.

Soil	Location	Cultivar	Kg/ha nutrients removed per tonne grain production		Reference
			N-P2O5-K2O		
Alfisol	Hyderabad	CSH 6	23-11-	0	J.B. Burford 1982*
Alfisol	Hyderabad	CSH 5	18- 8-27		Vijaya-lakshmi 1979
Vertisol	Akola	CSH 1	N- 9-32		Lakhdive and Gore 1978
Vertisol	Akola	CSH 1	27- 3- 0		Patil et al. 1974
Vertisol	Nagpur	CSH 4	24-10-34		Naphade and Choudhary 1974
Vertisol	Nagpur	CSH 1	18- 5- 0		Lanjewar and Khot 1977
Vertisol	Rahuri	CSH 5	21-10-52		Velayutham 1982**
Vertisol	Rahuri	CSH 8R	20- 8-22		Velayutham 1982**
Entisol	Kanpur	CSH 1	21- 9-23		Kumar and Awasthi 1977
Entisol	New Delhi	CSH 1	21-11- N		Sadaphal and Singh 1971
Entisol	New Delhi	CSH 1	27-11-23		Roy and Wright 1974
Entisol	New Delhi	CSH 1	N-14- N		Govil and Prasad 1973
Mean			22- 9-30		

* Personal communications (1982)

** Personal communications (1982)

N - Not reported

40 to 160 kg/ha N. At the highest N-level tested, soil + crop could account for 78.9% of added N, as compared with 93.2% at 40 kg/ha N.

About half of the fertilizer N left in the soil after the crop season was found in the top 15 cm of the soil but, for quantitative estimates, sampling up to 120-150 cm depth was found to be necessary. Another interesting result was that the difference between "direct" and

"indirect" estimates of crop recoveries by sorghum was bigger in the Alfisol than in the Vertisol (ICRISAT 1983, Moraghan et al. 1983).

4.2.4 Nitrogen-moisture Relationships

A significant positive interaction between fertilizer and moisture is reflected in sorghum yields (Kanwar 1978; Nagre and Bathkal 1978; Reddy et al. 1978; Venkateswarlu and Rao 1978) and this interaction is reported to be generally stronger in an Alfisol than in a Vertisol (Kanwar 1978). Water application in the Alfisol probably compensates for its comparatively shallow depth and low moisture storage, as compared with the Vertisol. With 58 or 120 kg/ha N, grain yields in the nonirrigated Vertisol were similar to those in the Alfisol irrigated at 50% moisture depletion. However, depending on the site and seasonal characteristics, an Alfisol can produce a higher yield of sorghum than a Vertisol at the same location (ICRISAT 1983).

In Vertisols at Akola, irrigation increased sorghum yields in a season of 629 mm/yr rainfall but not in the following year when 1081 mm/yr rainfall was received (Nagre and Bathkal 1978). In the low-rainfall year, irrigation increased grain yield from 2.8 to 4.9 t/ha in the presence of 120 kg/ha N + 60 kg/ha P₂O₅. Yields in general were much lower in the high-rainfall year, which were attributed to long rainy spells, cloudy weather, and reduced sunshine. Losses of nitrogen through leaching and denitrification under excess moisture might also partly have explained the effect (Singh and Choubey 1972). This aspect has received little attention in research, i.e., while rainfall increases moisture supply it can reduce solar radiation for photosynthesis. These counteracting effects on crop growth and yield deserve investigation (as also pointed out in section 4.2.2).

In a 2-year study on an Alfisol, a yield potential of 3.8 t/ha was considered possible with fertilizer application, but sorghum yields without fertilizer remained below 0.7 t/ha. Yield differences between years with different rainfall are shown in Table 16 to demonstrate the role of added nutrients in optimizing a given amount of rainfall (Venkateswarlu and Rao 1978). It is probable that, due to the acute deficiency of P, yields could not be raised beyond 1 t/ha because P was not applied together with N.

The above studies, and other estimates, show that N application increases the water-use efficiency significantly. In an irrigation experiment application of 120 kg/ha N increased water-use efficiency by 30% (Singh and Bains 1971). In rainfed sorghum placement of N increased grain yield by 400 kg/ha and moisture-use efficiency by 13% (Singh and Ramakrishna 1974).

Table 16. Productivity of rainy-season sorghum CSH 5 on an Alfisol as affected by fertilizer, in two seasons of different rainfall

Applied fertilizer		Grain yield (t/ha)		
N	P ₂ O ₅	1975	1976	Difference
(kg/ha)		(1184 mm/yr)	(677 mm/yr)	
0	0	0.67	0.41	0.26
40	0	0.97	0.58	0.39
0	40	1.70	0.62	1.08
40	40	2.77	1.71	1.06
80	40	3.82	2.21	1.61
CD.	(0.05)	0.596	0.356	

Source. Venkateswarlu and Rao 1978.

4.2.5 Times of Nitrogen Application

Results in this area have been quite variable. This may be because the relative merit of single application versus split application of N is not a fundamental issue but rather a site-specific outcome of soil texture, crop duration, rainfall pattern, and the total quantity of the N in question.

Findings of AICSIP and some other sources did not show any overall yield advantage from applying N in two splits (one-half basal one-half at knee-high stage) over all basal, and either of the two practices is advocated (Singh et al. 1974, 1981 b; Singh and Singh 1975; Warsi 1973). In experiments on farmers' fields, grain yields were higher when N was applied in two equal splits than when all of it was applied at planting (Mahapatra et al. 1973a).

In many trials, application of N in two splits gave up to 700 kg/ha extra yield over all N applied as basal for sorghum hybrids (Choudhari and Bapat 1976; Lingegowda et al. 1971; Patil et al. 1978; Sharma et al. 1979; Turkhede and Prasad 1978). In one report an application of 60 kg/ha N, all as basal, was optimum for CSH 1 (110 days duration), but split applications were superior for CSH 2 that took 125 days to harvest (Patil et al. 1972b).

Research results also suggest that sorghum yields may be significantly reduced (1) if basal application of N is omitted or reduced below 50% of total N, even though less than 10% of the total dry-matter is produced in the 1st month (Lingegowda et al. 1971; Patil et al. 1972b; Singh and Singh 1975), and (2) if a top-dressing of N is delayed beyond flower primordial stage (Choudhari 1978; Choudhari and Bapat 1976; Hussaini and Rao 1968b; Warsi and Wright 1973b). Split application of N can reduce leaching losses of N in years of high rainfall (Venkateswarlu et al. 1978), as already illustrated in Figure 9.

Split application of N in the rainy season is a recommended practice (AICRPDA1982). In this case it seems that the realities of rainfed farming have received precedence over reported yield gain data whether statistically significant or not. The yield advantages associated with split application of N make it a worthwhile practice because of the small cost of top-dressing N. Split application also provides an element of flexibility to the farmer for matching N applications with prevailing crop and weather conditions (Venkateswarlu 1979).

4.2.6 Methods of Nitrogen Application

Research in this area has been aimed at comparing either soil application versus foliar application of N or broadcast versus placement of N.

In multilocation trials by AICSIP from 1968 to 1977, foliar application of N did not prove superior to soil application (Singh et al. 1981 b; Singh and Singh 1975). In experiments on farmers' fields, application of 50 kg/ha N in two splits to the soil or half N at planting + half as a foliar spray, were on a par for rainfed sorghum (Mahapatra et al. 1973a). Under dryland conditions, soil application of N is now widely advocated (AICRPDA 1982). The situation has been summed up thus: "In case of nitrogen, in contrast to common belief, the weight of experimental evidence with irrigated as well as unirrigated sorghum and millet shows that foliar application does not prove in any way superior to soil application method" (Kanwar 1978). A foliar spray application of N is seen as a possible means of combating certain exigencies or of correcting N stress at a critical stage of crop growth.

Placement of N has been found to be superior over broadcast application, giving yield advantages of 300-500 kg/ha (Das and Subbiah 1975; Rathore and Dave 1979; Singh 1976), and increasing moisture-use efficiency (Singh and Ramakrishna 1974). In five trials in different soils of Andhra Pradesh, placement of 80 kg/ha N + 40 kg/ha P₂O₅ increased the grain yield of CSH 1 by 0.4 to 2.6 t/ha with a mean value of 1.1 t/ha as compared with broadcast application (Venkateswarlu 1979). The value of this extra yield alone comes to approximately twice the total cost of the fertilizer applied.

In recent studies on Alfisols and Vertisols, a "band-split" method of application gave significantly higher grain yields and crop recoveries of added N in both the soils, as compared with methods such as the broadcast incorporation or surface broadcast of N (ICRISAT1983; Moraghan et al. 1983). The band-split method involved half amounts of N placed 5 cm deep and 8 cm from opposite sides of plant rows at 4 and 19 days after emergence. As compared with the broadcast incorpo-

ration of N, the band-split method gave an extra 1.1 t/ha grain in the Vertisol at 72 kg/ha N and 1.5 t/ha extra grain in the Alfisol at 80 kg / ha N. It may be noted that the band-split application of N, apart from being labor-intensive and relatively complicated, actually is a combined effect of three factors: i.e., placement, subsurface application, and split application. Nevertheless, yield gains of 1.0-1.5 t/ha demonstrated by these experiments comprise substantial improvements.

4.2.7 Sources of Nitrogen

Common N-carriers such as urea, ammonium sulphate and calcium ammonium nitrate have been found to be on a par for rainy-season sorghum (ENSP 1971; Naphade and Chaudhary 1974; Verma 1961). In a recent report from an experiment on a Vertisol, crop recovery of added N was higher with NaNO₃ as compared with urea, while the fertilizer-N present in the soil after harvest of the crop was higher in the case of urea (Moraghan et al. 1983). This subject is now of minor research interest because the major nitrogenous fertilizer in use is urea and the important problems are rate of application, suitable methods of application, and timing for optimizing efficiency.

Several materials (slow-release, coated- and nitrification-inhibitor treated fertilizers) have been evaluated in field trials with CSH 1 under irrigation. These were I.B.D.U., A.M. fertilizers, urea mixed with cakes of neem, or karanj⁴ and urea coated with S, lac or neem cake (Kulkarni et al. 1975a). All materials were inferior to or statistically on a par with prilled urea. The critical difference values were rather high at 0.8-1.1 t/ha. In other reports, also, S-coated urea showed no advantage over ordinary urea, even on relatively light-textured soils for sorghum (Gunaseena and Ahmed 1979; ICRISAT 1977). In one case, urea neem cake gave lower yields than ordinary urea (Reddy et al. 1977). Evaluation of supergranules of urea for sorghum is under investigation (C.W. Hong, ICRISAT, personal communication 1982; ICRISAT 1983).

There are two reports which suggest that insecticides BHC and Thimet could retard the rate of nitrification in the soil, particularly in the early stages after application. Soil treatment with these agrochemicals resulted in higher N uptake by sorghum (Akotkar and Deshmukh 1974; APAU 1976). In a Vertisol at Akola, NH₄ + NO₃ nitrogen in the soil, grain yield, and total N uptake by sorghum all increased up to an application of 20 kg/ha BHC beyond which there was a decline in all these parameters (Fig. 10).

4. Neem = *Azadirachta indica*; karanj = *Pongamia glabra*.

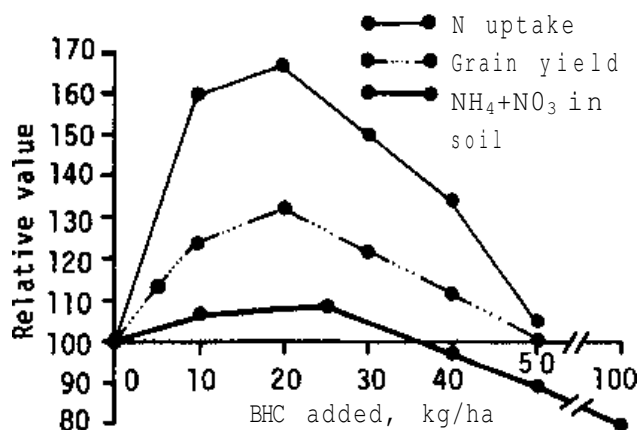


Figure 10. Effect of BHC on the nitrogen availability and uptake by sorghum CSH 4. (Akotkar and Deshmukh 1974.)

4.2.8 Nitrogen and Plant Population

Where moisture is not a constraint, an optimum level of 135000-270000 plants/ha in combination with 100-150 kg/ha N is suggested (Joshi and Upadhyay 1977; Narasiah et al. 1972; Patil and Surve 1980; Singh and Bains 1972; Singh et al. 1974; Singh et al. 1981 b). The optima for plant population as well as N for purely rainfed crops are both lower than the above ranges (AICRPDA 1982). The importance of an optimum plant population has been stressed because "no input can compensate the deficiency of low plant densities" (Singh et al. 1981a). In certain rainfed environments, e.g., at Dharwar, grain yield of CSH 1 continued to increase up to 666000 plants/ha, and the optimum was reported as 150 kg/ha N + 333000 plants/ha (Kudasomannavar et al. 1980a).

4.2.9 Residual Effect of Nitrogen

The residual effect of N applied to sorghum on the succeeding wheat was nonsignificant (Venkateswarlu et al. 1978). In another study, N application to sorghum increased yield of the succeeding oat crop (Srivastava and Singh 1970). In this case, sorghum grain yields were 1.0-1.3 t/ha, suggesting suboptimal use of N by the sorghum itself. Measurements of nitrate-N in the soil have been reported to give some indication of the residual N fertility (Hunsigi and Patil 1972; Srivastava and Singh 1970).

From experiments with ¹⁵N-labeled fertilizer it has been shown that, although considerable fertilizer N was present in the soil profile after the harvest of rainy season sorghum, this residual N was of limited value either for safflower grown in the postrainy season, or for sorghum grown in the following rainy season

(Moraghan et al. 1983). Three percent or less of the 74 kg/ha N added to rainy-season sorghum was recovered in the succeeding crop of safflower or sorghum.

4.3 Phosphorus

Phosphorous deficiency is widespread in the soils of the Indian SAT, as summarized in Table 3. Critical levels for sorghum by soil type, however, have not been worked out.

4.3.1 Yield Response to Phosphorus

Responses of sorghum to P application have been extensively reported, and P application is generally recommended (AICRPDA 1982). Experiments by AIC-SIP suggest a mean optimum level of 40 kg/ha P₂O₅ for rainfed sorghum (Singh et al. 1981b). A consolidated summary of responses to P application under field conditions is provided in Table 17. The overall quantum of response is in the order Alfisols > Entisols > Vertisols. Grain yield responses of 7-20 kg/kg P₂O₅ have been obtained in Vertisols. It is also being recognized that, to generate the same quantum of response, Vertisols may require higher P application than other soils because of their high clay content and greater reactive surfaces/components (Rao and Das 1982). There are reports that, in a particular area, response to P may be obtained on farmers' fields but not on research stations in the same area (Singh et al. 1974).

A useful tool of data interpretation is lost when research workers do not report the available P-status of experimental plots, whether responses are obtained (see Table 17) or not—as in trials at Kota and Parbhani (Khybri and Singhal 1977; Shekhawat et al. 1972; Tatwawadi and Choudhari 1976). However, some relationship between P soil tests and responses to P application for the Entisols can be seen from Table 17. It is interesting to note that, under good growth conditions at available soil-P levels of 13-16 kg/ha P₂O₅, an Entisol could support a yield level of 3.5-4.0 t/ha whereas an Alfisol could support a yield level of 1 t/ha. In both cases, an additional grain yield increase of 2-3 t/ha was obtained with P application in the presence of adequate N (Govil and Prasad 1972; ICRISAT 1981; Roy and Wright 1973b; Venkateswarlu and Rao 1978).

It appears that at similar initial levels of Olsen-extractable P, a Vertisol can support a higher yield of sorghum than an Alfisol. In addition, response to added P was much greater in the Alfisol (113%) than in the Vertisol (22%), even when the soil available-P was 3.1 ppm in the Alfisol and 1.4 ppm P in the Vertisol (ICRISAT 1983). The size and chemical reactivity of the P pools sustaining soil test values in these two types of soils require investigation.

Table 17. Response of rainy-season sorghum to phosphorus in field experiments.

Soil	Location (years)	Available P (P ₂ O ₅ , kg/ha)	Cultivar	P ₂ O ₅ added (kg/ha) ¹	Grain Response (kg/ha P ₂ O ₅)	Reference
Alfisol	Hyderabad (4)	14.6	CSH 6	46	32.4	JR. Burford ² 1982
Alfisol	Hyderabad (2)	13-16	CSH 5	80	28.3	Venkateswarlu and Rao 1978
Alfisol	Bhavanisagar (3)	?	Hybrid	60	16.7	Goswami and Singh 1976
Vertisol	Hyderabad (2)	?	CSH 1	63	19.7	ICRISAT 1974
Vertisol	Akola (2)	"Medium"	CSH 1	60	13.8	Lakhdive and Gore 1978
Vertisol	Akola (2)	"Low"	CSH 1	60	9.0	Nagre and Bathkal 1979
Vertisol	Rajkot (2)	"Low-Med."	CSH 6	30	10.9	Parmar 1979
Vertisol	Rahuri (1)	25.6	CSH 1	60	7.3	Patil and Shinde 1979
Vertisol	Rahuri (1)	25.6	CSH 5	60	9.2	Patil and Shinde 1979
Vertisol	Indore (3)	?	Hybrid	60	24.7	Goswami and Singh 1976
Vertisol	Siruguppa (3)	?	Hybrid	60	27.4	Goswami and Singh 1976
Entisol	New Delhi (2)	"Low"	CSH 1	60	24.3	Roy and Wright 1973b
Entisol	New Delhi (2)	12.6	CSH 1	60	20.7	Govil and Prasad 1972
Entisol	New Delhi (2)	12.6	CSH 1	60	19.3	Turkhede and Prasad 1980
Entisol	New Delhi (2)	20.9	CSH 1	60	11.3	Sadaphal and Singh 1971
Entisol	Kanpur(2)	8.0	8-B	30	34.3	Gupta et. al. 1973
Alfisol-Vertisol	Jhansi (3)	?	CSH 1	40	18.5	Mishra and Singh 1978

1 Source of P single superphosphate in all experiments except Govil and Prasad (1972). where it was triple superphosphate

2 Personal communication (1982)

Sorghum genotypes exhibited differential response to P and their ranking for P responsiveness was closely similar to their ranking for grain yield potential (Fig. 11). This may be a manifestation of the fact that higher yield potentials can be achieved only by supplementing native soil fertility.

From available data, as plotted in Figure 12, the role of P in improving the harvest index of sorghum is clearly shown. The implication is that, with adequate P, plants

can partition a greater proportion of the additional dry-matter produced into the grain and thus use the absorbed P more efficiently. This role of P needs wider recognition.

Phosphorus increases grain yield primarily by producing more grains, as is the case with N. Its effect on increasing the 1000-grain weight is much smaller (Table 18).

Apart from genotype, soil type, and the soil's initial

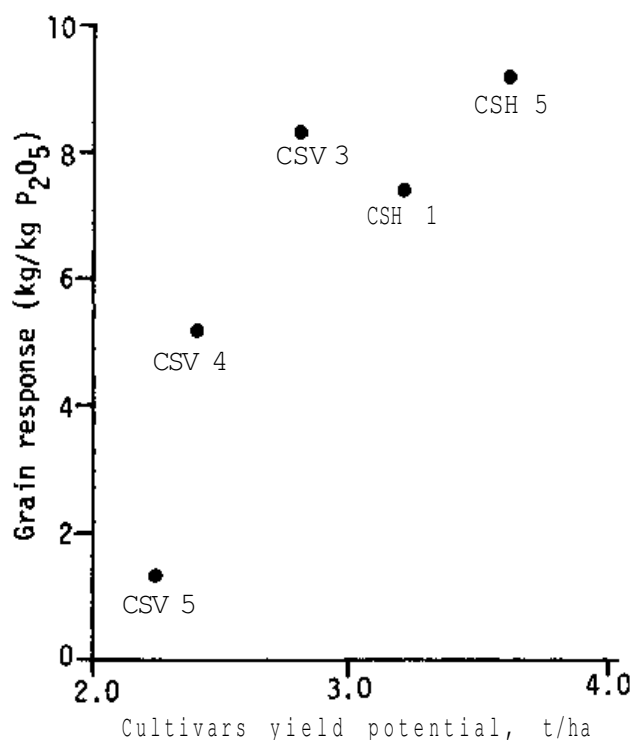


Figure 11. Association between yield potential of sorghum genotypes and their responsiveness to phosphorus. (Patil and Shinde 1979.)

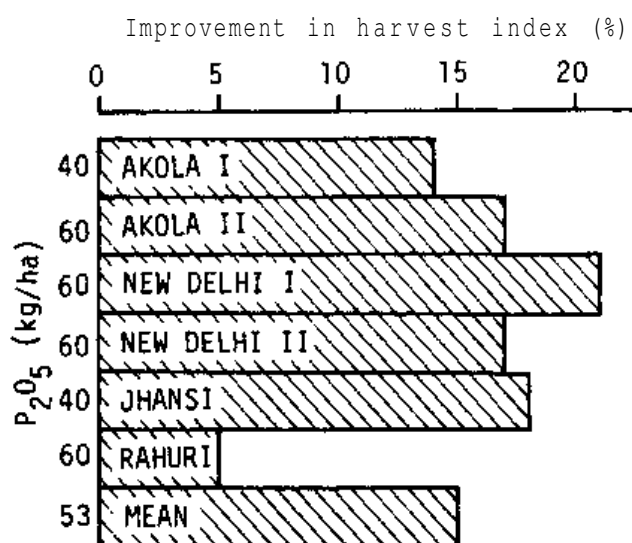


Figure 12. Improvement in the harvest index of hybrid CSH 1 as a result of phosphorus application.

fertility status, two other factors that affect the response of sorghum to P are (1) level of N applied, and (2) the environment for optimal crop growth. Some data on the N x P interaction are shown opposite (Fig. 13). It is con-

Table 18. Effect of phosphorus application on some grain yield characters of sorghum hybrid CSH 1.

Character	% increase at 60 kg/ha P ₂ O ₅ over no P ¹	
	Range	Mean
Grain no./ear	16-46	28
Grain wt/ear (g)	27-50	42
1000-grain weight (g)	1-12	5

Sources: Govil and Prasad 1972; Roy and Wight 1973a; Sadaphal and Singh 1971. Turkhede and Prasad 1980

¹ Average over levels of N

sidered appropriate to visualize responses to P as joint responses to NP. There is evidence that, at a given location, response to P is higher in a year when conditions favor high yields as compared with a year when yields are restricted for any reason (Bathkal et al. 1970; Dahatonde and Adhaoo 1978; Nagre 1981; Venkateswarlu and Rao 1978). The P x rainfall relation for two locations is illustrated in Figure 14. It seems desirable to

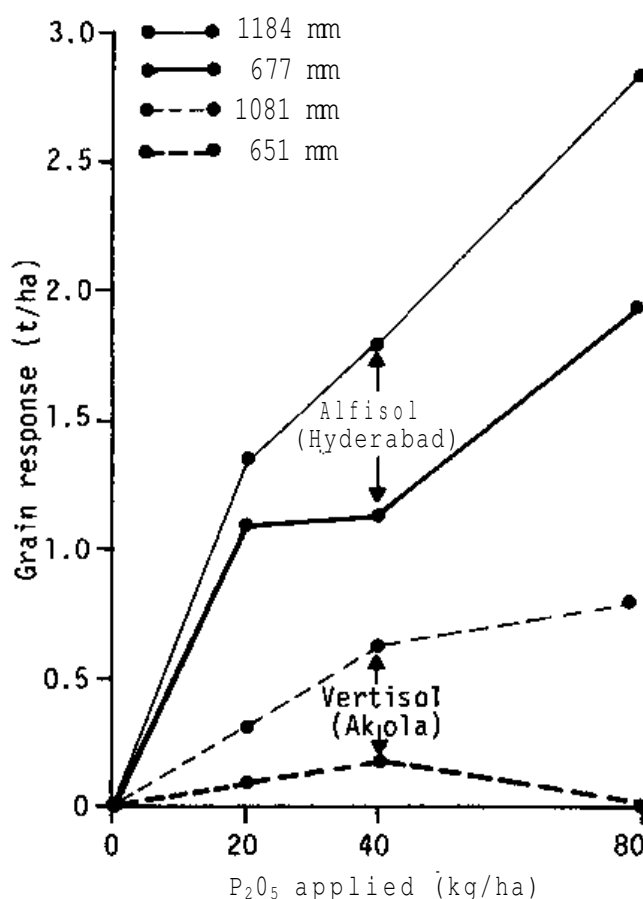


Figure 14. Response of sorghum to phosphorus in years of differential rainfall at two locations. (Dahatonde and Adhaoo 1978; Venkateswarlu and Rao 1978.)

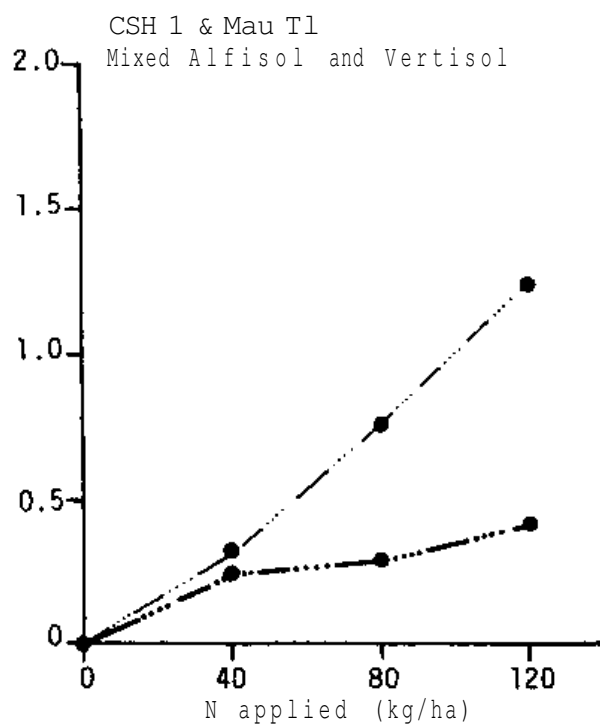
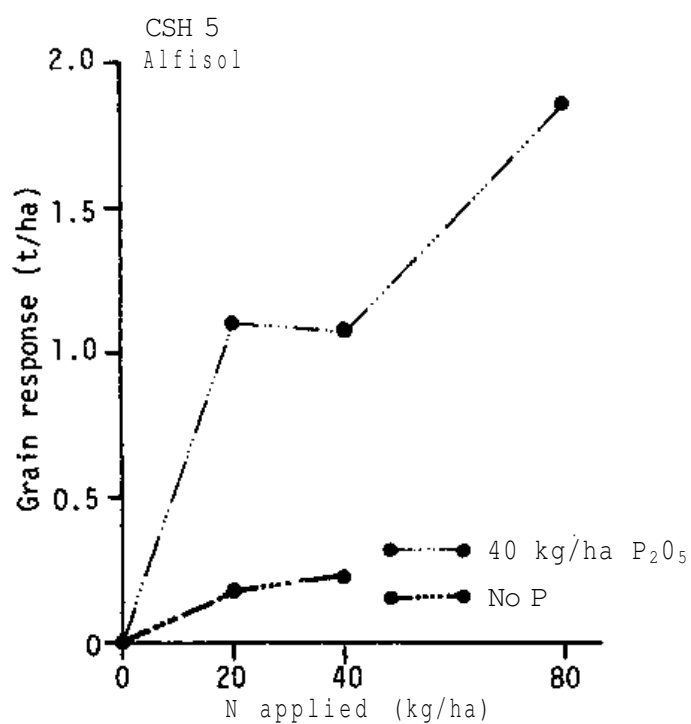
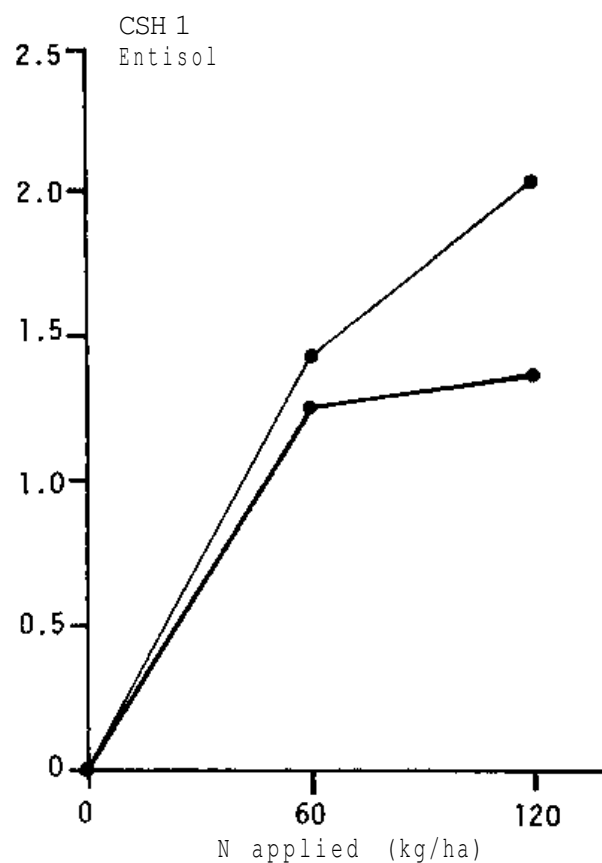
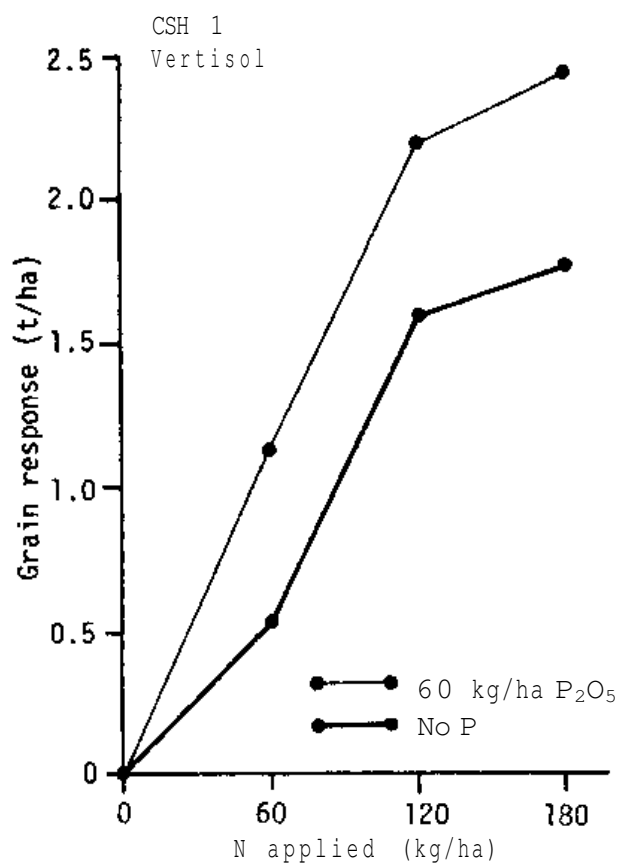


Figure 13. Nitrogen x phosphorus relationships in hybrid sorghum at four locations in the rainy season. (Mishra and Singh 1978; Nagre and Bathkal 1979; Roy and Wright 1973b; Venkateswarlu and Rao 1978.)

try to quantify environmental effects on nutrient response rather than to average the responses over different environments. The large volume of data on fertilizer responses clearly suggests that it is advantageous to undertake only well-characterized medium- to long-term fertilizer experiments specifically for P and K (ICRISAT 1983).

4.3.2 Uptake of Phosphorus

High-yielding cultivars of sorghum remove about 9 kg/ha P_2O_5 to produce 1 t/ha of grain (Table 15). Total P uptake by a local cultivar (NJ-156) was 40% more than by hybrid CSH 1, but the latter produced 40% more grain due to its superior harvest index (Lanjewar and Khot 1977, 1978). Judged on the basis of grain yields, efficiency of P is much higher in HYCs than in traditional cultivars.

Utilization of added P increases markedly with N application (Govil and Prasad 1974; Kumar and Awasthi 1977; Lakhdive and Gore 1978; Lanjewar and Khot 1977; Patil et al. 1974; Roy and Wright 1974; Sadaphal and Singh 1971; Srivastava 1971; Turkhede and Prasad 1980). In a 2-year experiment in an Entisol deficient in N and P, the P uptake was 9.8 kg/ha P in the unfertilized plots. This uptake increased by 50% with the application of N and by 171% with the application of both N and P (Roy and Wright 1974).

Hybrid CSH 1 continued to absorb P up to a time approaching maturity (Govil and Prasad 1974), there being a particularly rapid rate of uptake during the 84-91 day period preceding maturity (Roy and Wright 1974). Over 90% of the net gain in P uptake from N + P plots over N plots was recorded in the earheads.

4.3.3 Sources of Phosphorus

Some comparisons have been made of the relative performance of different P-carriers for sorghum. These have generally concerned sources containing different proportions of water-soluble forms of P (APAU 1976; Govil and Prasad 1972; ICRISAT 1977; Lakhdive and Gore 1978; Mahapatra et al. 1973b; Prithvi Raj et al. 1975; Shaikh and Zende 1971b; Upadhyay and Yenpredeniwar 1971). A comparison of nitrophosphate containing 30% of its P as water-soluble, with superphosphate from nine neutral-alkaline soils, is presented in Figure 15. The experimental cultivars were HYCs in all cases, and the experiments at Indore, Akola, and Dharwar (all Vertisols) were rainfed. Broadly speaking the comparison shows that, in six out of nine cases, nitrophosphate gave a higher response than superphosphate. In four comparisons reported from Akola, Gwalior, and Siruguppa (Mahapatra et al. 1973b) 50%

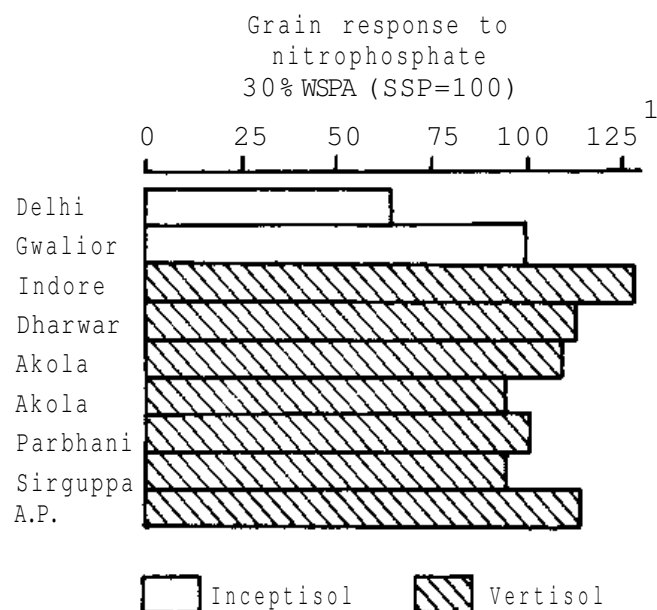


Figure 15. Comparison of nitrophosphate with superphosphate for HYC sorghums in field experiments.

water-soluble P gave no yield advantage over 30% water-soluble P.

In several studies on the sources of P there were no plots with N only. This means that the evaluation amounts to a combined NP effect (Mahapatra et al. 1973b; Prithvi Raj et al. 1975; Upadhyay and Yenpredeniwar 1971). Attention is also drawn to the interactive effect of the water solubility of phosphate and the particle size of the P-carrier. In a pot experiment (Shaikh and Zende 1971 b) and a field trial (Govil and Prasad 1972), dicalcium phosphate (DCP) performed better than nitrophosphate of 30% water-soluble P. In research, DCP is generally used in powder form while nitrophosphates are granulated, and the two materials offer vastly different surface areas for reaction with soils at equivalent levels of P.

Rock phosphate has been found inferior to superphosphates as a source of P for sorghum in field experiments in Entisols (Govil and Prasad 1972) and in Alfisols (ICRISAT 1977).

4.3.4 Methods of Phosphorus Application

It is generally recommended that all P fertilizer should be applied as basal, and deep-placed rather than broadcast (AICRPDA 1982). Tracer studies showed that phosphorus derived from fertilizer (Pdff) increased with deep placement in a noncalcareous soil but decreased in a calcareous soil (Venkatachalam et al.

1969). Possibly different reaction products were formed in the two soils, and the rooting environment may also have been different.

In a trial on hybrid CSH 1 in an Entisol, P applied as basal was found to be on a par with the split application of P. The "top-dressing" of P in this case was "band placement 4-6 cm deep in the soil" during crop growth (Turkhede and Prasad 1980). In another study, also at IARI, band placement of granular triple superphosphate (TSP) and TSP mixed with seed gave grain yield increases of 340 kg/ha and 590 kg/ha respectively, as compared with P broadcast (Sadaphal and Singh 1971). All these trials confirm the prevailing consensus that, for sorghum, all P should be applied basal and preferably deep-placed.

4.3.5 Residual Effects of Phosphorus

As double cropping under rainfed conditions is not a common practice, data on the carryover benefit of a P application are available only where irrigation has been applied to one or both of the crops in the sequence.

In a 3-year study with a sorghum-wheat sequence in Vertisols at Indore and Siruguppa⁵, sorghum was more responsive than wheat to the direct application of P. It was also an equal or better user of residual P applied to wheat (Goswami and Singh 1976). Similar trends were observed with the sorghum-pearl millet sequence in Alfisols. Wheat (postrainy season) was more sensitive than sorghum (rainy season) to nutrient stress (Soni and Mukherjee 1980).

In Vertisols at Akola and Nagpur, P applied to sorghum did not influence the yield of the succeeding wheat or cotton (Morey 1968; Morey and Nagre 1980). However, in another trial at Akola the effect of P applied to sorghum on wheat yields was quite variable among P sources and years (Lakhdiva 1979).

In one study at IARI, New Delhi, response of sorghum to P applied to the preceding crop of wheat was significant only in the 2nd year of the wheat-sorghum sequence. Sorghum yields were of a much lower order in the 1st year, however (Prasad et al. 1981). In another 2-year study, also at IARI, the residual effect on wheat of P applied to sorghum was significant in the 1st year only, and these effects were similar for triple superphosphate and dicalcium phosphate or for DCP and nitrophosphate with 30% water-soluble P (Prasad and Govil 1974). The increase in the rotational uptake of P from these experiments is shown in Table 19.

In the final analysis of the rotational response to P, economics plays a decisive role because the value of different crops in a system is not equal. If wheat and

Table 19. Grain yield and phosphorus uptake in a sorghum-wheat cropping sequence as affected by P application to sorghum.

Year	P applied (TSP) to sorghum (kg/ha)	Sorghum		Sorghum & wheat	
		Grain yield (t/ha)	Total P uptake (kg/ha)	Grain yield (t/ha)	Total P uptake (kg/ha)
1968	0	4.09	24.1	6.24	36.3
	26	6.31	34.7	8.94	49.0
	Difference	2.22	10.6	2.70	12.7
1969	0	3.49	20.8	6.00	34.5
	26	4.11	27.8	6.87	43.2
	Difference	0.62	7.0	0.87	8.7

Source: Govil and Prasad 1972; Prasad and Govil 1974.

sorghum prices are taken as Rs 150 and Rs 120 per 100 kg respectively, then a yield response of 100 kg/ha of wheat is as good as a 125 kg/ha yield response in sorghum. Cropping systems research, therefore, cannot be interpreted only in terms of changes in yield. The economic dimension also needs to be considered simultaneously.

4.4 Potassium

4.4.1 Yield Response to Potassium

Except in the soils of the Bundelkhand region (Jhansi), yield responses of sorghum to K application have generally been small or statistically nonsignificant (Bathkal et al. 1970; Kalbhor and Girase 1971; Khybri and Singhal 1977; Nagre 1981; Nagre and Bathkal 1979; Shekhawat et al. 1972; Singh et al. 1981b; Tatwawadi and Choudhari 1976; Zende 1978a). At Jhansi, response to K application has been obtained with local cultivar Mau-T1 (Gahlot et al. 1979) and also with hybrid CSH 1 (Gill and Abichandani 1976). Application of 60 kg/ha K₂O increased the grain yield of CSH 1 by 10.5 kg per kg of K₂O. Potassium responses on farmers' fields have been reported from Vertisols or associated soils in Gulbarga, Osmanabad, Chitradurga and Dhule districts (Krishnan 1978). It seems that at the present level of cropping, K-deficiency may not be serious for sorghum-growing areas but with higher yields and more intensive cropping, this situation is expected to change.

In a long-term experiment established in 1979 on an Alfisol, responses of sorghum to K application started emerging in the 1981 crop. Grain yields of sorghum were 4.0 t/ha with an application of 120 kg/ha N, 4.6 t/ha with 120 kg/ha N + 30 kg/ha K, and 5.0 t/ha when 120 kg/ha each of N and K were applied (ICRISAT

5. Not necessarily the best environments for wheat production.

1983). Thus K increased grain yield by almost 1 t/ha in the presence of N in the 3rd year of this experiment.

4.4.2 Uptake of Potassium

Mean removal of potash by sorghum per tonne of grain production is 30 kg K₂O (Table 15). Generally more K per unit yield is removed from Vertisols than from other soil. Yield increases brought about by NP application result in the increasing removal of soil K, as already shown in Figure 8.

Potassium absorption by hybrid CSH 1 continued to increase up to 90 days, after which there was a 14-18% loss of K from the crop (Roy and Wright 1974). Potassium uptake and crop growth were reduced at extreme moisture treatments when sorghum was grown in a Vertisol in 1 -kg pots (Kharkar and Deshmukh 1976).

4.5 Secondary Nutrients

4.5.1 Sulphur

There are few data on the effect of S on sorghum in India. Soils from five locations in Maharashtra contained 13-44 ppm available S and were considered to be "well-supplied" with this element (Patil et al. 1977). In Nau-bauer tests on a Vertisol containing 8.2 ppm water-soluble S as SO₄, sorghum CSH 4 responded to S application (Badhe and Lande 1980). In a sandy loam having 10 ppm available S, dry-matter and S-uptake of CSH 1 increased with the application of S. The 55-day-old crop removed 14% of applied S, as determined from ³⁵S-analysis (Singh et al. 1976b).

4.5.2 Calcium and Magnesium

Perhaps because of the high base saturation of most soils where sorghum is grown in India, not much work has been done on Ca and Mg in the nutrition of sorghum. Hybrid CSH 1 grown as a rainfed crop on a Vertisol at Akola, removed 28.6 kg/ha Ca and 16.6 kg/ha Mg for a yield level of 2.6 t/ha (Lakhdiva and Gore 1978).

4.6 Micronutrients

Although the deficiency of Zn is considered to be more extensive than that of any other micronutrient, very little systematic research work has been carried out specifically on this deficiency in the sorghum crop. While over 58000 soil samples have been analyzed (J.C. Katyal, All India Coordinated Scheme of Micronutrients for Soils and Plants, personal communication 1982) there were no samples from Maharashtra, where about 40% of the

sorghum area in India is located. An earlier report based on 550 analyses from that state is available, however (Patil et al. 1972a).

Field results from two sets of multilocation experiments are available from AICARP trials (Singh et al. 1979). In one set, response of sorghum HYCs to the foliar spray of Zn, Fe, Mn, Cu, B, and Mo was studied in 20 experiments at 12 locations during the years 1967-71. In the second set, response of HYCs of sorghum to the soil application of Zn, Mn, Mo, and their combinations was studied in 13 trials at 4 locations during 1971-77, and also the residual effect on wheat following sorghum. Basic soil analyses for these fields have not been reported; hence correlation of responses with soil fertility is not possible. Further, in 19 out of 37 experiments, the coefficient of variation was 15% or higher.

4.6.1 Zinc

Percentages of soil samples found deficient in Zn are given in Table 20. Earlier work considered Maharashtra soils not to be deficient because analyses showed there was over 0.5 ppm available Zn (Patil et al. 1972a). But recent studies, though few, indicate that the critical level of Zn for sorghum, particularly in Vertisols, may be closer to 1.0-1.2 ppm dithizone-extractable Zn (Kene and Deshpande 1979; More et al. 1977; Takkar and Randhawa 1980).

In refined sand culture the critical level at which a 50% response to Zn could be expected was 15 ppm Zn in 35-day old plants of CSH 1 (Katyal and Agarwala 1982). In a pot culture with a sandy loam soil, 6-week old CSH 1 plants contained 21 ppm Zn but still showed a 60% increase in dry-matter when further Zn was added (Shukla et al. 1973).

Differential response of sorghum genotypes to Zn stress has been demonstrated by growing nine cultivars in a loamy sand soil containing 0.3 ppm dithizone-extractable Zn (Shukla et al. 1973). Their findings are illustrated in Figure 16. This study shows that:

1. genotypes containing 17-32 ppm Zn at the 6-week stage could respond to Zn application;
2. dry-matter response to Zn application among genotypes varied from 48 to 183%;
3. genotypes that were more efficient in utilizing soil Zn for dry-matter production did not respond beyond 2.5 ppm added Zn, while the "less efficient" types responded up to 5 ppm added Zn;
4. regardless of whether dry-matter increased or not the uptake of Zn continued to increase with Zn application in all genotypes and, as an average over

Table 20. Micronutrient deficiencies¹ in soil of major sorghum-growing states of India.

State	Zinc		Copper		Manganese		Iron	
	Samples analysed ('000)	Samples deficient (%)	Samples analysed ('000)	Samples deficient (%)	Samples analysed ('000)	Samples deficient (%)	Samples analysed ('000)	Samples deficient (%)
Andhra Pradesh	2.8	54	2.1	0	2.1	1	3.0	1
Gujarat	11.1	26	11.1	8	11.1	2	11.1	11
Haryana	8.5	74	7.8	2	6.5	14	6.8	20
Karnataka	2.2	21	2.2	4	2.2	1	2.2	1
Madhya Pradesh	4.6	58	3.7	2	3.8	8	4.0	7
Maharashtra ²	-	-	-	-	-	-	-	-
Tamil Nadu	4.3	32	4.3	3	4.0	16	4.5	17
Uttar Pradesh	4.9	57	3.9	1	3.6	1	4.4	6
All India	58.2	47	50.4	1	47.2	5	49.5	11

Source: Katyal, J.C., personal communication, 1982

1. General deficiency rating, not particularly for sorghum.

2. Data for Maharashtra state, from the All India Coordinated Scheme of Micronutrients in Soils and Plants, are not available

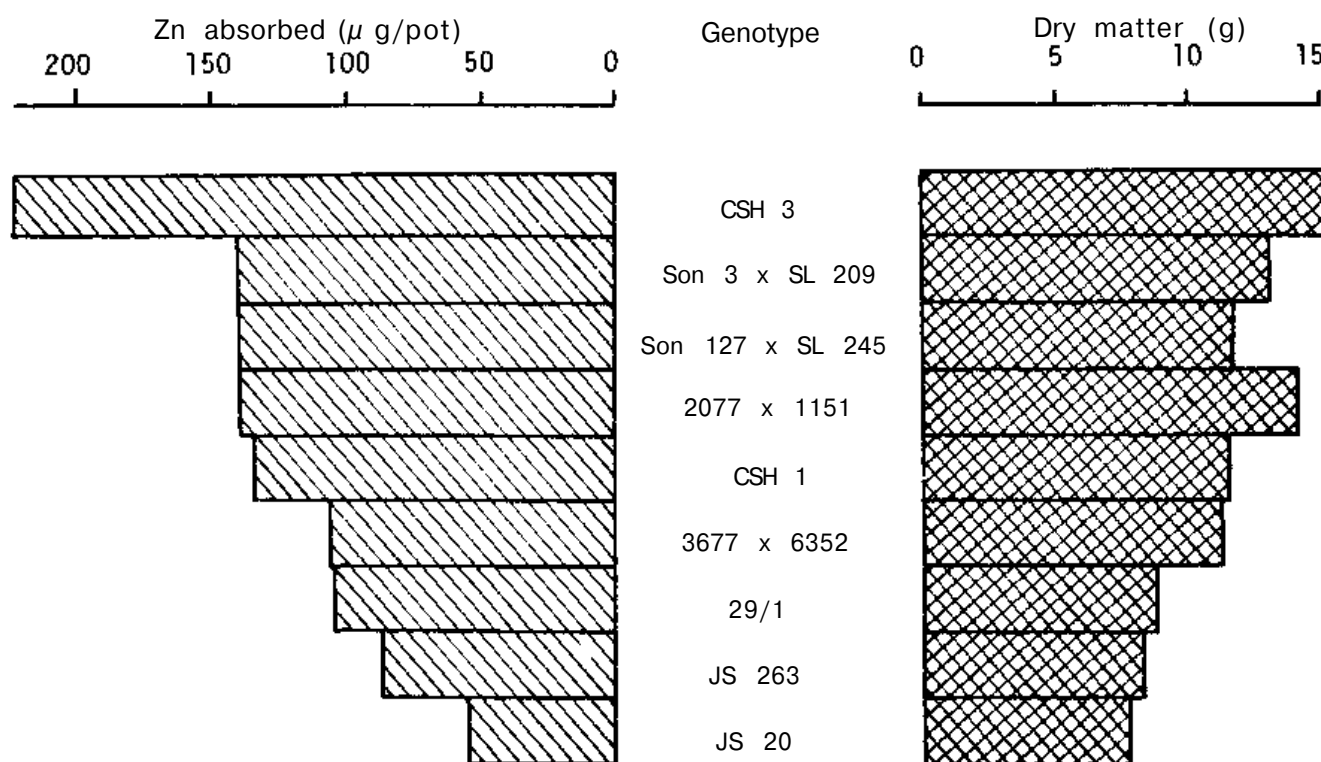


Figure 16. Differential response of nine sorghum genotypes to zinc stress and to Zn application derived from a pot culture in a loamy sand with 0.275 ppm available Zn. (Shukla et al. 1973.)

entries, at 2.5 ppm and 5 ppm levels of applied Zn increase in dry-matter was 63% and 89% respectively, while the corresponding increase in Zn uptake was 248% and 427%; and

5. hybrid CSH 3 was found to be most tolerant of Zn stress because it maintained the highest tissue concentration and uptake at all levels. Hybrid CSH 1 was intermediate. High-yielding variety Swarna (CSV 1) is

also considered relatively tolerant to Zn deficiency (Randhawa and Takkar 1976; Subba Rao 1975).

At research stations, significant responses to Zn have been reported from Akola, Indore, and Nandyal. In Vertisols, grain responses of hybrid sorghum to Zn application were significant in soils containing 0.26-0.82 ppm available Zn but nonsignificant in a soil containing 1.1 - 1.2 ppm available Zn (Kene and Deshpande 1979; Khan and Zende 1976; More et al. 1977). No response was obtained in an Oxisol containing 1.7 ppm available Zn. In a Vertisol containing 0.26 ppm available Zn, sorghum responded to Zn only after the acute deficiency of P had been corrected by P application (Khan and Zende 1976). In another Vertisol at Parbhani, having 1.2 ppm available Zn, yield response of irrigated CSH 4 to Zn was not significant, but Zn uptake continued to increase with the application of Zn. A crop producing 1.9 t/ha of grain removed 172 g/ha of Zn (More et al. 1977). Zinc deficiency has also been reported from the Nandyal tract of Andhra Pradesh. The soils there, which are Vertisols planted in the late rainy season (maghi), contain 0.5-0.8 ppm dithizone-extractable Zn (I.V. Subba Rao, Andhra Pradesh Agricultural University, Bapatla, personal communication 1982). A yield increase of 410-540 kg/ha was obtained from Zn application in a soil containing 0.6 ppm available Zn (Rao and Parthasarathy 1971; Subba Rao 1975).

In one set of 20 experiments grain yields were not affected by a foliar spray of Zn. But, in another series of 12 trials, soil application of 50 kg/ha ZnSO_4 produced grain yield increases of 0.6-1.1 t/ha in 3 out of 6 years in the Vertisols at Indore over recommended rates of NPK under nonirrigated conditions (Singh et al. 1979).

Data from 305 experiments on farmers' fields in eight districts show that there was a significant and consistent response to Zn application in Chitradurga and Jalgaon districts (Kulkarni et al. 1979; Singh et al. 1979). In the mixed Alfisols-Vertisols of Chitradurga, an irrigated crop of CSH 1 gave average increases of 460 kg/ha, and CSH 5 gave a grain yield increase of 760 kg/ha to Zn application. In Vertisols in Jalgaon, hybrid PSH 2 (CSH 4) gave a consistent response to Zn with (+340 kg/ha) or without (+230 kg/ha) irrigation. It may thus be concluded that, in most sorghum-growing areas, particularly in Vertisols, Zn deficiency is common and significant responses to Zn application can be expected. ICRISAT experience has shown that, when the soil is leveled or old bunds are demolished, Zn deficiency for sorghum becomes serious. Deficiencies of Zn and P are the first to be noticed.

4.6.2 Iron

Deficiency of Fe is next to that of Zn in frequency of occurrence, the incidence being 11 % and 20% in Guja-

rat and Tamil Nadu (Table 20). As compared with pearl millet, sorghum is considered to be more sensitive to Fe deficiency and less efficient in the absorption/translocation of Fe; it consequently has higher requirements than pearl millet (Bisht et al. 1978). The HYCs of sorghum as a group were considered to be sensitive to Fe stress, and chlorotic leaves were found to contain higher concentrations of P, K, and B but were lower in Fe and Mn as compared with healthy leaves (Subba Rao 1975).

Considerable variation in response to Fe stress among sorghum genotypes has been reported. In solution culture, genotypes IS-84, IS-3691, and M-35-1 were found to be tolerant to Fe stress whereas CK60B, KS-5A, and KS-5B were least tolerant (Kannan 1980b). Cultivars CSH 5 and 2077-A could tolerate Fe stress and recover from it but others, including CSH 6, could not. No correlation was observed between ^{59}Fe -uptake and tolerance of Fe stress (Kannan 1980a). Evidence for heterosis in recovering from Fe stress has been presented because hybrids CSH 7 and CSH 8 were found to be more tolerant than their parents (Kannan 1981).

Iron application increased sorghum yields in (1) a loamy sand containing 0.48 ppm available Fe (Chahal et al. 1978), (2) a sandy soil of pH 7.9 containing 1.17 ppm available Fe (Singh and Yadav 1980), and (3) a calcareous clay soil of pH 8.4 containing 1.02 ppm available Fe (Babaria and Patel 1981). In the latter experiment application to CSH 5 of 20 ppm Fe as $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ increased grain yield by 0.9 t/ha, and a 3.7 t/ha grain crop removed 1.37 kg/ha Fe (Figure 17). A 31 % increase in yield due to Fe application was accompanied by a 61 % increase in Fe uptake (Babaria and Patel 1981).

In Vertisols at Akola having 4.2-7.8 ppm available Fe, no response to Fe application was observed in 2 years of a field trial with CSH 1 (Kene and Deshpande 1979). Iron uptake in sorghum decreased with increasing levels of CaCO_3 (Patil and Patil 1981). In pot experiments with soils containing 3.0-4.7 ppm available Fe, both CSH 5 and CS-3541 (CSV 4) responded to Fe application, and the response was higher when FeSO_4 was mixed with cotton-leaf compost as compared with FeSO_4 alone (Francis and Rajagopal 1978; Francis and Subbiah 1978). In 20 field experiments foliar application of Fe increased sorghum yield in 1 out of 20 cases (Singh et al. 1979). Moisture regimes and genotypes, in addition to soil analysis, are important data to take into account in predicting iron deficiency.

Antagonism of Fe with Zn, Mn, and Cu has been reported (Singh and Yadav 1980). Manganese did not reduce the uptake of Fe but probably interfered in chlorophyll synthesis (Kannan and Joseph 1975). Increasing levels of Cu reduced Fe concentration in the leaves

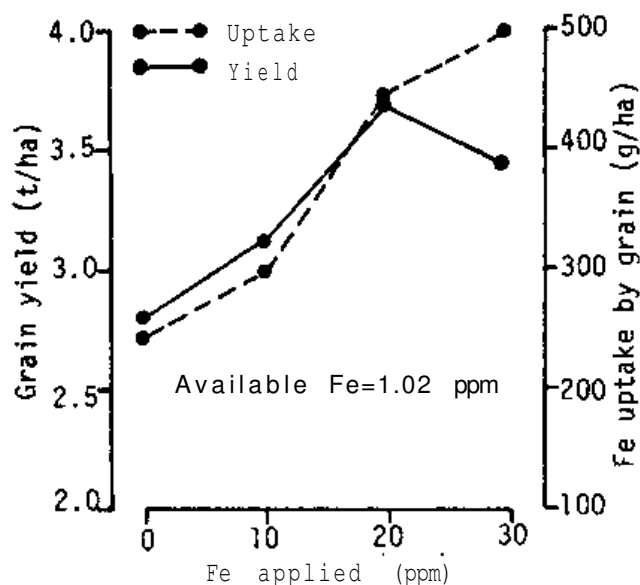


Figure 17. Response of sorghum hybrid CSH 5 to iron application in a calcareous clay soil. (Babaria and Patel 1981.)

and ears of sorghum but not in the stem or roots (Gopalakrishnan 1960). A P:Fe ratio of 5.5:1 in 30-day-old sorghum plants was stated to be critical, below which level yields decreased because Fe possibly reduced the uptake of P by sorghum roots (Chahal et al. 1978).

4.6.3 Manganese

The deficiency of Mn is relatively common in the soils of Madhya Pradesh and Tamil Nadu (Table 20), but some soils of Maharashtra and Andhra Pradesh are also reported to be deficient (Patil et al. 1972a, Subba Rao 1975). About 50% of 237 soil samples from alkaline areas of Maharashtra were termed "low to critical" (Patil et al. 1972a). Likewise, deficiencies of Mn for sorghum have been noted in light-textured mixed Alfisol-Vertisols at Hyderabad (Subba Rao 1975).

In four Vertisols available Mn was negatively correlated with free CaCCX_3 . Manganese concentration in 3-week old plants of M-35-1 increased with increase in available Mn, but dry-matter yields remained unaffected (Bhor et al. 1970). Addition of CaCCh led to a decrease in Mn concentration in CSH 5 plants only at flowering stage although it decreased Fe content at all stages of plant growth (Patil and Patil 1981).

Hybrid CSH 5 removed 100 g/ha Mn per 1 t/ha grain production in an Alfisol (Vijayalakshmi 1979). In pot experiments with refined sand, the critical level for Mn in 35-day-old plants was reported as being 12 ppm (Katyal and Agarwala 1982).

In field experiments the response of CSH 1 to Mn application was significant in 1 out of 3 years in Vertisols at Akola which contained 124-130 ppm active Mn fraction (Kene and Deshpande 1979). Other workers also reported lack of response to Mn in similar soils (Deshmukh et al. 1974; Patil et al. 1972a).

In a 1-year trial at Jhansi application of 10 kg/ha MnSO_4 in two sprays increased the grain yield of CSH 1 by 0.78 t/ha (Gill and Abichandani 1972). In the other 19 experiments in this series, at 11 centers, there was no response of sorghum to Mn. At Indore soil application of Mn increased yields in 1 out of 4 years (Singh et al. 1979).

4.6.4 Copper

Deficiency of Cu seems to be of some importance in Gujarat where 8% of the 11000 soil samples were found to be deficient in available Cu (Table 20). The critical level of Cu in 35-day-old sorghum plants was reported to be 2 ppm (Katyal and Agarwala 1982).

In a sandy soil containing 0.19 ppm DTPA-extractable Cu, antagonism of Cu with Fe and Zn and its synergism with Mn has been reported (Singh and Yadav 1980). In sand culture increasing levels of Cu from 0 to 100 ppm decreased the Fe and Mn content of Co.12 plants in particular. As Cu levels increased, Fe concentration decreased in leaves at all stages of growth up to harvest, and also in the earheads, but the reverse was the case in stems and roots, which showed that their Fe content increases with increasing levels of Cu (Gopalakrishnan 1960). In 20 field experiments the response of sorghum to foliar applications of Cu was nonsignificant in 18 cases, positive in one and negative in another case (Singh et al. 1979).

4.6.5 Boron

A critical level of 7 ppm B in 35-day-old sorghum plants has been reported, based on data from pot experiments with refined sand (Katyal and Agarwala 1982). In plants suffering from Fe chlorosis an increase in B content of more than x3 in comparison with healthy leaves was observed (Subba Rao 1975). Out of 20 experiments at 12 locations foliar application of B increased sorghum yield in two cases (Singh et al. 1979). It is thus evident that, generally, responses to B application cannot be expected.

4.6.6 Molybdenum

A survey of 550 soils from Maharashtra reported available Mo contents from trace to 4 ppm. In the 700-900 mm/yr rainfall zone with dark brown or black calcare-

ous clay loams, 55% of 161 soil samples contained less than 0.12 ppm available Mo and were categorized as "low to critical" (Patil et al. 1972a).

Foliar application of Mo increased sorghum yield in 1 out of 2 years at Indore and in 1 out of 3 years at Akola (Singh et al. 1979). In trials where Mo was applied to the

soil, significant yield increases (0.9-1.35 t/ha) were obtained in Vertisols at Indore in 2 out of 4 years and at Akola in 1 out of 2 years.

As a summary to section 4.6 it can be concluded that, among the micronutrients, deficiency of Zn is the most widespread, but that Mn and Fe deficiencies also occur.

5. POSTRAINY-SEASON AND SUMMER-SEASON SORGHUM

Close to 95% of the 6.5 million ha under postrainy-season sorghum are located in the states of Andhra Pradesh, Karnataka, and Maharashtra (as depicted in Fig. 1b and enumerated in Table 1). During the 1970s a recommendation to plant at dates earlier than those normally used by farmers when growing their postrainy-season crops has resulted in substantially higher yields. Advancement in the time of seeding improved cultivars by up to 1 month has brought about yield increases of 0.5 t/ha to 3.0 t/ha (Randhawa and Venkateswarlu 1980; Spratt and Chowdhury 1978). Yield improvements of this magnitude will obviously affect the efficiency of all inputs, including fertilizer, and thus nutrient management is considered to be one of the components of improved dryland technology (AICRPDA1982). Sorghum yields have been shown to increase $\times 4$ - $\times 10$ depending on improvements made in terms of cultivar, fertilizer, and soil and water management (Sahrawat et al. 1979; Sanghi and Rao 1982; Vijayalakshmi 1979). It is difficult to comment on how many reported experiments were conducted in accordance with the improved concepts of dryland management developed during recent years. But the adoption of these management practices would obviously influence the yield gains obtained from fertilizer application.

5.1 Nitrogen

5.1.1 Yield Response to Nitrogen

A mean response of 15 kg grain per kg N at 60 kg/ha N has been reported over eight trials conducted by AICRPDA (Venkateswarlu 1979). Significant responses were obtained from 60-100 kg/ha N at 13.3 kg/kg N under nonirrigated conditions, when data from different available sources had been assessed, whereas the optimum N level for irrigated postrainy sorghum is in the range of 100-150 kg/ha N, with a mean response of 18.5 kg grain per kg N (Chowdhury and Chetty 1979; Deshmane et al. 1979; Hariprakash 1979; ICRISAT 1974; Kalbhor and Girase 1971; Krishnamurthy et al. 1975; Patil et al. 1981; Pawar et al. 1980a; Ramakrishna et al. 1974; Ramshe et al. 1977; Rao and Reddy 1978; Rao et al. 1978; Rao and Parthasarathy 1971; Umrani 1979; Umrani and Bhoi 1981). Response to N can vary widely depending upon the rainfall received during the crop season (Patil et al. 1981; Umrani and Bhoi 1981).

As postrainy-season sorghum is largely supported by the soil's stored moisture, soil texture, slope, and depth become major deciding factors in determining the

amount of moisture available for crop use. Published data from experiments on Vertisols indicate a 1 t/ha yield difference between a "deep" and a "shallow" soil. This is illustrated in Figure 18, which is based on results from Bijapur and Solapur (the districts in which postrainy-season sorghum is grown in over 1.2 million ha). Depending upon soil depth and available moisture storage, the optimum level of N at Solapur varied from 25 to 85 kg/ha N (Patil et al. 1981). The Solapur experience has been summarized thus: "The data reported so far would amply prove that, in drylands, fertilizer application is a tool to optimise soil moisture. There is less risk involved than is made out to be. Improving the management techniques⁶ is the pre-requisite" (Umrani 1979).

In Vertisols at ICRISAT Center the double cropping of sorghum was found to be feasible. Yield of postrainy-season sorghum (after a rainy-season crop of sorghum) without N was substantially reduced and was attributed to greater nitrogen stress. When N was applied, yields increased by 1.4 t/ha, as shown in Table 7 (Rego et al. 1982).

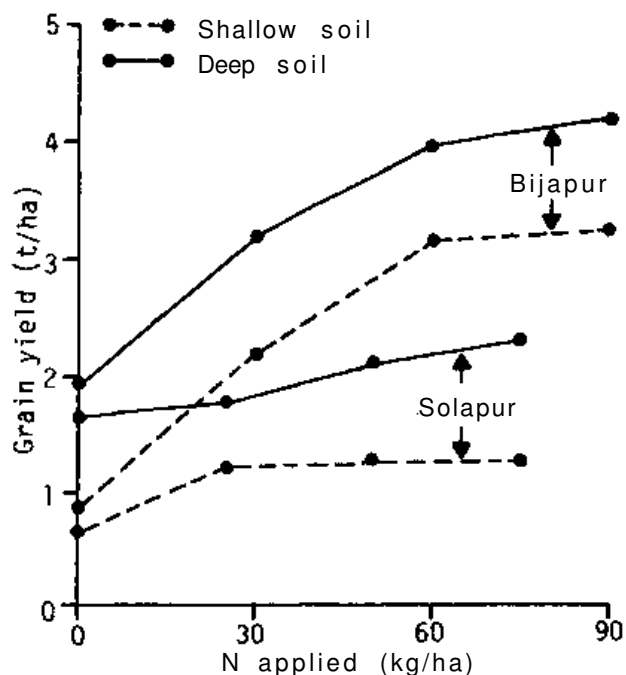


Figure 18. Performance of postrainy season sorghum as influenced by soil depth and N at two locations. (Havanagi 1979; Umrani 1979.)

⁶ Timely seeding; optimum plant population; fertilizer use and its placement; and weed control.

Varietal differences in response to N have been demonstrated in a 2-year experiment at Bijapur (Havanagi 1979). Responses to N varied from 5 to 26 kg grain per kg N, and N-responsiveness was directly proportionate to the yield potential of the cultivar (Fig. 19). The most widely grown cultivar (5-4-1) produced 0.7-0.9 t/ha less than CSH 8R and SPV 86. These HYCs outyielded local cultivars and CSH 1 at all levels of N. These data show that the HYCs were more efficient users of native as well as applied sources of nutrients. Several reports suggest that CSH 8R and SPV 86 are superior to other cultivars for the postrainy season (Havanagi 1979; Ramshe et al. 1977; Rao and Reddy 1978; Rao et al. 1978).

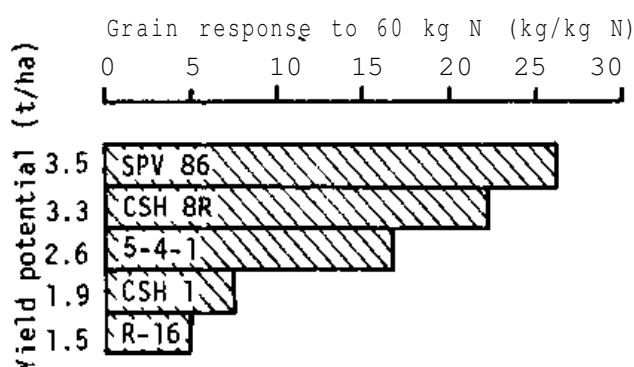


Figure 19. Differential response of sorghum genotypes to nitrogen and its application with the yield potential. (Havanagi 1979.)

The outcome of fertilizer trials on farmers' fields under AICARP have been given in Figure 7. In results from Bijapur and Dharwar districts sorghum yields were lower in the low-rainfall years and zones. The effect of moisture conservation ("putting a bund around the field and ploughing across the slope") on yields was marginal (Hiremath et al. 1977; Kulkarni et al. 1975b, 1977, 1978). As mentioned in the introduction to section 5 it is worth considering what would be the effect on fertilizer responses if seeding in these trials were to be advanced in accordance with improved technology recommendations, or if large-scale efforts were to be undertaken to provide "life-saving" irrigation.

5.1.2 Uptake of Nitrogen

The N content of 30- or 60-day-old plants was correlated ($r = 0.87$) with CSH 1 yields (Hariprakash 1979). A nonirrigated crop of CSH 1 at Parbhani, fertilized at 125-75-0 kg/ha of N-P₂O₅-K₂O produced 4.16 t/ha grain and removed 170 kg/ha N (Tatwawadi and Hadole 1972). Only 2.7% of the total N was absorbed in the first 37 days (much lower than in the rainy season), followed by a very rapid rate of N absorption—i.e. 88

kg/ha N was absorbed in the 38-69 day period at the rate of 3 kg N/day.

5.1.3 Forms of Nitrogen

Data from Bellary and Bijapur indicate that fertilizers containing nitrate performed better than others (Havanagi 1979). Nitrate-N appears to be a form of considerable importance for postrainy-season sorghum and the need to measure it in order to understand the availability of N in Vertisols is now suggested (Finck and Venkateswarlu 1982; Rego et al. 1982).

5.1.4 Times of Nitrogen Application

Many data show the advantages of applying all N as basal, preferably placed in the soil rather than broadcast or applied in splits (Havanagi 1979; Patil et al. 1981; Rao and Parthasarathy 1971; Venkateswarlu 1979). In experiments on farmers' fields the split application of N was found to be superior over all N as basal in several cases (Mahapatra et al. 1973a). Perhaps the advantages of a single or split application of N can be confirmed if related research into rainfall probabilities at different locations is undertaken.

5.1.5 Methods of Nitrogen Application

In Vertisols a 20-cm deep placement of N gave 1 t/ha extra yield as compared with a 10-cm placement, when a postrainy-season crop of sorghum was grown after a rainy-season crop, but there was no difference in the two depths when the postrainy-season crop was grown after a rainy-season fallow (Rego et al. 1982). This observation suggests there are different soil moisture profiles for the two intensities of cropping.

5.2 Phosphorus

5.2.1 Yield Response to Phosphorus

Data from field experiments suggest that, for moderate crop growth, a mean response of 11 kg grain per kg P₂O₅ may be expected in Vertisols if improved cultivars are grown and weather conditions are favorable (Table 21). At Solapur, cultivar M-35-1 has shown no response to P (Patil et al. 1981; Saharabuddhe and Bhatwadekar 1966), but an extra yield potential of almost 1 t/ha over local cultivars has already been demonstrated by hybrids at Solapur (Patil et al. 1981). At Bellary, response to P was significant in 1 out of 3 years when conditions were favorable for high yield (Havanagi 1979).

Table 21. Field responses of HYC sorghum to phosphorus in the postrainy season¹

No.	Soil (years)	Location (cultivar)	P ₂ O ₅ (kg/ha)	Grain response		Reference
				(t/ha)	(kg/kg P ₂ O ₅)	
1	Alfisol (2)	Hyderabad (CSH 1)	63	2.03	32	ICRISAT 1974
2	Vertisol (1)	Hyderabad (CSH 1)	69	1.45	21	ICRISAT 1974
3	Vertisol (1)	Bellary (?) ²	90	0.42	5	Havanagi 1979
4	Vertisol (2)	Bijapur (?)	60	0.48	8	Havanagi 1979
5	Vertisol (1)	Pune(CSH 1)	37	0.52	14	Kalbhor and Girase 1971
6	Vertisol (1)	Pune(CSH 2/M-35-1)	50	0.49	10	Nagre and Sahasrabuddhe 1977
7	Vertisol (2)	Pune(CSH 1/M-35-1) ³	50	0.45	9	Pawar et al. 1980a

1 All experiments nonirrigated, except no. 7. Source of P either single superphosphate or diammonium phosphate

2 Response to P in 1 out of 3 years when rainfall was favorable

3 Response to 75 kg/ha P₂O₅ over 25 kg/ha P₂O₅, as no zero-P treatment

In an irrigated trial at Pune, the yield increase with P application was 180 kg/ha in the presence of 50 kg/ha N and 450 kg/ha with 150 kg/ha N (Pawar et al. 1980a).

5.2.2 Uptake of Phosphorus

In 60-day-old plants, 0.23% P in the leaf was considered to be critical, and the P content was significantly correlated with yields (Hariprakash 1979).

Nonirrigated CSH 1 on a Vertisol at Parbhani removed 49.3 kg P₂O₅/ha to produce a grain yield of 4.16t/ha (Tatwawadi and Hadole 1972). Whereas cultivar M-35-1 removed 46.5 kg/ha P₂O₅ for a lower grain yield of 2.3 t/ha, there were also marked differences in the distribution of P absorbed by plants. In M-35-1, 51 % P was in the earhead as compared with 76% in CSH 1. It was also observed that 61 % of the total P was absorbed in the 38-69 day period by CSH 1, i.e., almost at the rate of 1 kg/day P₂O₅, and P uptake continued up to maturity. A 4.6 t/ha grain crop at Pune removed 37.4 kg P₂O₅—considerably less than the uptake under Parbhani conditions (Pawar et al. 1980b; Tatwawadi and Hadole 1972).

5.2.3 Sources of Phosphorus

Field data from Vertisols at Bellary and Bijapur show that superphosphate (0-16-0) and diammonium phosphate (18-46-0) were on a par as sources of P for sorghum

(Havanagi 1979). In the red loams of Bhavanisagar (Typic Ustorthents) nitrophosphates with 30% or 54% P in water-soluble form were on a par with superphosphate for Swarna (CSV 1) under irrigation (Mahapatra et al. 1973b). In pots and microplots in which ³²P-labeled fertilizers and variety CS 3541 (CSV 4) were used, triammonium and tetraammonium pyrophosphates performed better than conventional fertilizers, giving Pdff values of up to 35%. Ammonium nitrate phosphate with 70% water-soluble P was shown to be suitable for Alfisols and Vertisols (Subba Rao 1977).

5.2.4 Methods of Phosphorus Application

Deep placement of P has been found to be better than broadcast application. Accordingly, drilling of P is now generally recommended (AICRPDA 1982; Havanagi 1979; Patil et al. 1981; Venkateswarlu 1979; Vijaya-lakshmi 1979).

5.3 Potassium

Response of postrainy-season sorghum to K has generally not been obtained (Kalbhor and Girase 1971; Nagre and Sahasrabuddhe 1977; Sahasrabuddhe and Bhatwadekar 1966). In an experiment with irrigated sorghum, response to K increased with an increase in the level of N (Pawar et al. 1980a). In trials on farmers' fields, responses to K have been reported from Nizam-

abad area of Andhra Pradesh (Krishnan 1978) and up to 2.5 kg grain per kg K₂O from districts in Maharashtra (Zende 1978b).

On a deep Vertisol sorghum removed 128 kg/ha K in producing 4.46 t/ha grain under irrigation. The amount of K removed increased with increasing rates of NPK application, as expected (Pawar et al. 1980b).

5.4 Micronutrients

The response of postrainy-season sorghum to micronutrients has been either nonsignificant or inconsistent (Singh et al. 1979). Some results for the late rainy season (maghi) have been discussed in section 4.6.1.

5.5 Summer-season Sorghum

Most of the sorghum crop grown in the summer season (the January-May period) is irrigated primarily in Tamil Nadu but also in Andhra Pradesh and Karnataka. Potential areas for this crop have been identified as the Nagarjunasagar and delta areas of Andhra Pradesh and the Tungabhadra project area of Andhra Pradesh and Karnataka. Possibilities of raising sorghum as an intercrop with irrigated summer groundnut have also been suggested (Rao 1972).

5.5.1 Yield Response to Nitrogen

Grain yields up to 7 t/ha in clay loams and 6 t/ha in sandy loams can be obtained under high levels of management (Table 22). Data on optimum doses of N, response ratios, and other inputs are given in this table. The HYCs outyielded the locally-improved cultivars at different levels of fertility (Aaron et al. 1970; Rao and Reddy 1973).

5.5.2 Uptake of Nitrogen

In absolute terms, total N uptake by local and HYCs is similar, especially at low to moderate N levels, but it produces high grain yield only in the HYCs. The proportion of total N absorbed up to the boot leaf stage was reported to be higher in unfertilized plots and the content of grain protein increased from 9 to 11 % as a result of N application (Rao and Reddy 1973).

5.5.3 Nitrogen and Irrigation

Highest yields are obtained by the combined application of irrigation and nutrients (Fig. 20). A comparison between 7 and 16 irrigations revealed that a 1.1 t/ha increase in grain yield was due to irrigation alone,

Table 22. Optimum level of nitrogen-associated yield response and other inputs for summer-season sorghum in India.

Item	Hyderabad			Bhavanisagar	Coimbatore	Madurai
	1	2	3			
Soil	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Clay loam	Sandy loam
Cultivar	CSH 1	HYC	CSH 1	Swarna	CSH 5	CSH 5
Optimum N (kg/ha)	150	80	100	100	150	133
Yield at optimum N (t/ha)	6.93	5.94	3.21	5.06	7.08	4.92
Response to optimum N (kg/kg N)	16.8	48.1	14.2	34.2	13.3	24.4
P ₂ O ₅ applied (kg/ha)	75	?	50	45	45	Applied
K ₂ O applied (kg/ha)	ND	?	30	45	45	Applied
Irrigation	9	16	?	14	?	11 days
Remarks	138 000 plants/ha	Irrigated at 20% ASMD	Irrigated N in 2 splits	Irrigated at 50% ASMD 55 cm water	Irrigated N in 4 splits	Irrigated 42 cm water
References	Narasiah et al. 1972	Venkatachari et al. 1976	Rao and Reddy 1973	Kaliappa et al. 1974	Korikantimath and Palaniappan 1976	Kandasamy and Subramanian 1979

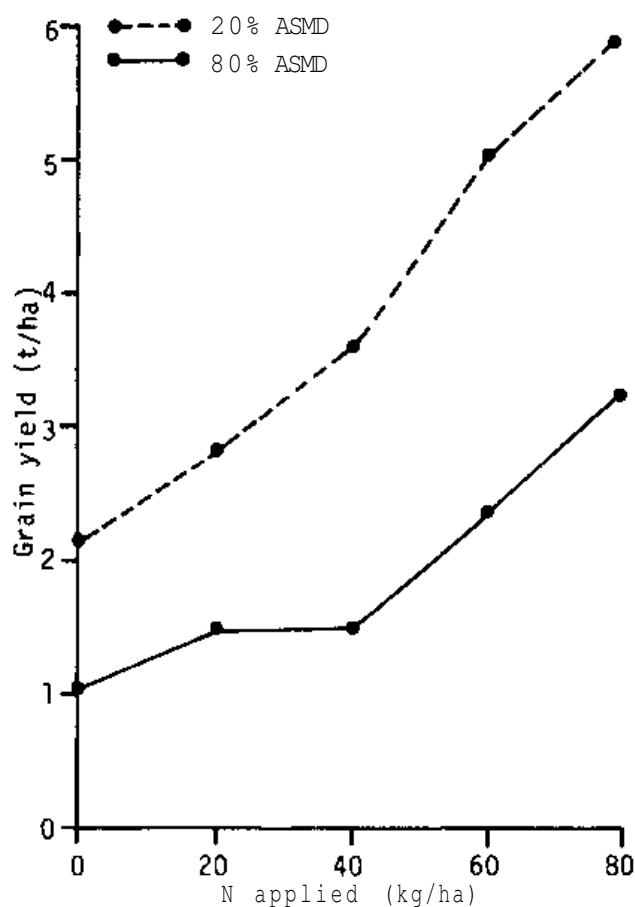


Figure 20. Synergistic effect of nitrogen and irrigation for summer sorghum. (Venkatachari et al. 1976.)

2.3 t/ha was due to 80 kg/ha N with 7 irrigations, and 4.9 t/ha was due to 80 kg/ha N with 16 irrigations. In another experiment at Bhavanisagar, also on a sandy-loam soil, sorghum yields were highest when irrigation was applied at 50% available soil moisture (Kaliappa et al. 1974). In another sandy loam 133 kg/ha N + 42 cm of

irrigation water was considered optimum for CSH 5 (Kandaswamy and Subramanian 1979).

5.5.4 Phosphorus

Application of 90 kg/ha P_2O_5 below the seed in a sandy loam soil (8.7 kg/ha available P) increased grain yield of CSH 1 by 2.1 t/ha over 120 kg/ha N + 60 kg/ha K_2O giving a response of 23 kg grain per kg P_2O_5 . When P was applied broadcast the response was 1.45 t/ha, or 30% lower. The crop which received P matured 1 week earlier (Chinnaswami et al. 1978).

5.5.5 Fertilizer Use on the Ratoon Crop

For raising a ratoon crop of hybrid sorghum in the summer, an application of 100-150 kg/ha N in two splits has been found to be best (Burhanuddin and Yassen 1974; Vijaykumar and Palaniappan 1977). A ratoon crop of CSH 5, when fertilized with 100 kg/ha N + 45 kg/ha P_2O_5 + 45 kg/ha K_2O produced a grain yield equivalent to that of the main crop in 84 days (5.8 t/ha). Thus in 189 days, one main crop of 5.8 t/ha grain, plus one ratoon crop of 5.9 t/ha grain could be harvested when both were fertilized at similar rates and ratios (Vijayakumar and Palaniappan 1977). Ratooning, however, creates serious pest and disease problems and is not a popular farming practice.

5.5.6 Results from Farmers' Fields

In 64 experiments on farmers' fields in Coimbatore district, grain yields above 6 t/ha were obtained by fertilizing CSH 1 with 120-60-0 or 120-30-30 kg/ha of N- P_2O_5 - K_2O (Aaron et al. 1970). Both CSH 1 and Co.18 responded significantly to fertilizers but, at any equivalent treatment with or without fertilizer, CSH 1 outyielded Co.18 by 1.7-2.2 t/ha. The response yardstick for CSH 1 was 9.4 kg grain per kg nutrient at 120-30-30, while for Co.18 it was 9.1 kg/kg nutrient at 60-30-0 kg/ha N- P_2O_5 - K_2O .

6. SUMMARY AND CONCLUSIONS

The area of sorghum cultivation in India is divided among the seasons as follows: rainy season, 60%; post-rainy season, 35%; and summer season, 5%. Of the total area, 95% has no irrigation. The use of HYCs has now reached 25% of the cropping area. Sorghum's share in the all-India consumption of fertilizer is probably less than 5%. The crop is grown on soils with a wide range of physical and chemical properties. Deficiencies of N, P, and Zn are widespread. The normal turnover of organic matter in soils of the SAT may make available up to 50-70 kg/ha N/yr, but it is not enough to meet the N requirements of a good sorghum crop. Moreover, losses of mineralized N through leaching, erosion and volatilization are also possible, though no quantitative estimates of such losses exist.

Most sorghum research has concerned the "rate and date" type of agronomy, and soil fertility studies have received less emphasis. There is very little precise information on the nutrient uptake and efficiency for well-characterized systems. Most of the work reported relates to CSH 1 (the first hybrid released in India, now being largely replaced with better hybrids and varieties). Field research has been valuable in (1) the multilocation evaluation of fertilizer responsiveness of new sorghum genotypes, and (2) the study of sorghum agronomy and fertilizer responses providing guidance on the nutrients limiting grain production, the potential yields of cultivars, and the soil and other environmental constraints affecting production. The information thus far available has demonstrated the need for fertilizing sorghum in order to obtain good yields under rainfed conditions.

6.1 Broad Conclusions

6.1.1 Grain yield potentials of up to 5.5 t/ha in Entisols and Vertisols and of 3-4 t/ha in Alfisols have been repeatedly demonstrated, averaged over several years. Increases in grain yields from $\times 4$ to $\times 10$ can be achieved by the integrated use of improved cultivars, fertilizer, and soil and water management combined with agronomic adjustments such as timely seeding, optimum plant stand, etc. The HYCs have outyielded the traditional cultivars at all levels of management in all seasons. The reviewers have no reservation in stating that there is sufficient research information to raise overall yield levels to 2.0-2.5 t/ha from the present level of less than 1 t/ha. Perhaps an IADP-type effort, as launched in the 1960s, is required in those 24 districts which account for 50% of the all-India sorghum area to insure that proven technology, inputs, advice, and follow-up

are made available (Appendix 2). We see no scientific reason why sorghum yields should not increase in the coming years if suitably coordinated steps are taken at all levels.

6.1.2 A 5.5 t/ha grain crop of hybrid sorghum removed 335 kg/ha of nutrients (149 N + 61 P₂O₅ + 125 K₂O kg/ha). On average sorghum removes 22 kg N, 9 kg P₂O₅ and 30 kg K₂O to produce 1 t of grain. Thus, to obtain good yields, it is necessary to use fertilizers because one cannot depend on the nutrient supply from the soil alone.

6.1.3 Sorghum-based intercropping systems have been shown to offer improvements in yield, production stability, and economic returns, but there is relatively little information available on the fertilizer needs of these systems.

6.1.4 In deep Vertisols, where moisture may be available for a second crop in the post-rainy season, sorghum or other suitable crops can be successfully raised only with fertilizer use.

6.1.5 Although it is said that rainfed crops are largely raised in intercropping systems, statistics on area and production are invariably still tabulated on a sole-crop basis, and very little research has been done to establish the areas occupied by different cropping systems.

6.1.6 Significant yield increases due to fertilizer application have been obtained under a variety of soil-climatic conditions, and fertility management (N, P, Zn) is as important as water management.

6.1.7 Two major factors that determine the quantum of yield response to fertilizers are a genotype with a high yield potential and an environment with minimal constraints affecting plant growth.

6.1.8 Some data suggest that *Azospirillum*, and other microorganisms such as mycorrhizae, are useful yield-enhancers. But, in view of inconsistent experimental results and low responses, it is considered that more critical studies are needed before recommendations concerning their use can be given.

6.1.9 Nitrogen increases the percentage of protein in grain (as expected because protein is taken as N \times 6.25). But improvement in the quantity and quality of sorghum protein is not linked because of the negative

relationship between protein and lysine (the most limiting essential amino acid).

6.1.10 Moisture availability (precipitation and profile storage) is a major determinant that influences sorghum yield and the crop's response to fertilizer. It has been more talked about than monitored in fertility research so far. Yield can increase up to 1 t/ha with an increase in soil depth/moisture storage in the postrainy season. Fertility and moisture increase each other's efficiency.

6.1.11 Genotypes vary in their responsiveness to N, P, Zn, and Fe. Generally hybrids and improved varieties show greater sensitivities than other cultivars to any stress associated with these nutrients, and they express their full potential in the presence of a proper balance of these nutrients. Gene action for N uptake was reported to be additive, while for P uptake and nitrate reductase (NR) activity it was nonadditive. Cultivars with deep root systems were relatively more tolerant of drought, while those containing a high level of K seemed tolerant of salinity.

6.1.12 In a soil highly deficient in Zn, there was a 4-fold difference among nine genotypes in the quantity of Zn absorbed, and the optimum level of added Zn was lower for the more efficient types. Likewise, hybrids differed in their response to Fe stress and, while some were reported to be heterotic for ion uptake (Rb), others were heterotic for the translocation of the absorbed Rb. In Vertisols and Vertic type soils, which are extensively used for sorghum production, Zn and Fe deficiencies and their amelioration deserve attention. Data suggesting that Mn deficiencies occur are available from Madhya Pradesh and Maharashtra.

6.2 Conclusions for Rainy-season Sorghum

6.2.1 A well-fertilized crop continues to accumulate dry-matter and nutrients up to maturity, while growth and nutrient uptake ceases earlier in an unfertilized crop. Generally, the rate of N accumulation is faster than that of dry-matter in the early stages of growth, and the reverse is the case in the reproductive phase.

6.2.2 The optimum rate of N application for rainfed HYC sorghums varies from 60 to 120 kg/ha N, when a mean response of 18.3 kg grain per kg N is obtained, the break-even response being 4.2 kg/kg N at current prices (nitrogen Rs5/kg; sorghum grain Re1.20/kg). Intralocation variations in response to N can be very

large, even for the same cultivar, with the result that making a meaningful interpretation of the data remains a research challenge. Straightforward relationships of yield with seasonal rainfall or the soil's organic carbon content do not emerge from published data.

6.2.3 In soils deficient in N and P, both nutrients increase the other's response, efficiency, and uptake. "Apparent" crop recoveries of fertilizer N established by the difference method can be 55-105%. In experiments with ^{15}N it was observed that out of 74-80 kg/ha added N, sorghum recovered 62.5% N in the Alfisol and 55.0% in the Vertisol. The crop + soil system accounted for 89.6% of fertilizer N in the Alfisol and 93.6% in the Vertisol. Almost half of the residual N was located in the upper 15 cm of the soil. The difference between direct and indirect measurements of crop recovery of added N was bigger in the Alfisol when compared with the Vertisol. Availability of the residual N to the next rainy-season crop was less than 3%.

6.2.4 A split application of N to the soil is generally useful. In a year of excessive rainfall a split application of N was shown to result in improved recoveries of N by the crop. Even though less than 10% of the total N is absorbed in the 1st month after seeding, sorghum yields are adversely affected if the dose of N at planting is either reduced to less than 50% of the total dose, or the top-dressing is delayed beyond the flower primordia stage.

6.2.5 The main contribution to higher yields from N as well as from P application comes from an increase in the number of grains per panicle, which show a mean increase of 60%.

6.2.6 Various slow-release N-carriers, coated materials, nitrification inhibitors, etc., have shown no advantage for sorghum over ordinary prilled urea in the limited number of experiments conducted so far.

6.2.7 Interaction between moisture and N is generally positive and significant, but not always so. Yields are not necessarily high in seasons of high rainfall. Much depends on the distribution of rainfall in relation to the stage of the crop and its effect on the dynamics of mineralized N present in the soil before the rainy season starts. This aspect, as well as the counteracting effects of prolonged or untimely rains (more water but less solar radiation), have yet to be fully investigated.

6.2.8 Significant yield responses to 30-60 kg/ha P_2O_5 have been obtained in different soils. These are in the range (kg/kg P_2O_5) of 11-34 in Entisols, 17-33 in Alfi-

sols, and 7-27 in Vertisols, the average order of response being Alfisols > Entisols > Vertisols. Phosphorus application improves the harvest index and, as in the case of N, the main factor for higher yield is increase in the number of grains per panicle. In Alfisols, particularly, P-deficiency can severely limit the response to N.

6.2.9 Apart from soil type, response to P is strongly influenced by the yield potential of the cultivar, level of N applied, available soil P, and a favorable environment for a moderate to high yield. P uptake increases with higher N and P application and, for a given value of available P in the soil, an Alfisol supports lower yield than an Entisol/Inceptisol or a Vertisol.

6.2.10 Rock phosphate proved inferior to superphosphate for sorghum in an Alfisol. Nitrophosphate compared fairly well with superphosphate except in the Entisol. In many published reports the effects of N and P or of water-solubility and particle size are not separable.

6.2.11 Drilling of P provides a significant yield advantage over its broadcast application. The residual response of P applied to sorghum on the following crop (generally wheat is studied) is small and not consistent. Rotational responses can be meaningfully interpreted only on the basis of the economic value of the component crops and nutrient-use efficiency.

6.2.12 Response of sorghum to K has so far been rare, except in the mixed Alfisols-Vertisols of Jhansi region and in cultivators' fields from parts of Karnataka and Maharashtra. In a long-term experiment on an Alfisol, K application increased sorghum grain yield by 1 t/ha in the 3rd year in the presence of 120 kg/ha N.

6.2.13 A number of experiments on the response of sorghum to micronutrients do not report the status of available nutrients and are therefore difficult to interpret. It appears that the critical level of Zn for sorghum, specially in Vertisols, may be around 1.0-1.2 ppm DTPA-extractable Zn. Field responses to Zn application have also been obtained in the Nandyal area of Andhra Pradesh and in Chitradurga and Jalgaon districts. In the field, sorghum responded to Fe application in a Vertisol containing 1 ppm available Fe. In soils containing 3-5 ppm available Fe, responses were obtained in pots but not in the field.

6.2.14 A differential response of sorghum genotypes to the stresses of Zn and Fe have been demonstrated and are summarized in section 6.1. Higher rates of Cu application reduced the concentration of Fe in leaves and ears but increased the Fe content of roots and

stems. Leaves suffering from Fe-chlorosis accumulated more B than healthy leaves.

6.2.15 It is also evident that, in sorghum fields, particularly in the rainy season, weeds are very serious competitors for available nutrients as well as for moisture. Weed control is thus essential to improve the efficiency of fertilizer applied to sorghum.

6.3 Conclusions for Postrainy-season Sorghum

6.3.1 The early accumulation of N in the postrainy season appears to be slower than in the rainy season. Grain yield increases of 13-15 kg/kg N have been obtained from the application of 60-100 kg/ha N. For an irrigated crop application of 100-150 kg/ha N results in a mean response of 18.5 kg grain per kg N.

6.3.2 The optimum level of N for sorghum can vary from 25 to 85 kg/ha N with increasing soil depth and moisture storage capacity. The yield difference between a "shallow" and a "deeper" soil was almost 1 t/ha. There are hardly any studies where fertility and moisture in the postrainy-season sorghum have been monitored and reported together. There seems to be no justification for studying fertility and moisture separately because, in a season where the moisture for growing the crop is largely stored, there is a source:sink type of relationship between rainfall and the soil profile, which profoundly affects the other source:sink represented in the plant.

6.3.3 In deep Vertisols the double cropping of sorghum is possible, and respectable yields can be obtained if N is applied.

6.3.4 A response of 11 kg grain per kg P₂O₅ is obtained in a Vertisol where an HYC is grown and the environment is favorable for a moderate to good yield. P-responsiveness of genotypes is of the same order as their yield rank.

6.3.5 Deep placement of N and P has been found to be necessary for the efficient use of nutrients. In a deep Vertisol the optimum depth of placement for N was influenced by the distribution of available moisture in the profile.

6.3.6 The amount of research done on postrainy-season sorghum is small in relation to the crop's area of cultivation (6.5 million ha)—more than that of pearl millet or maize, for example.

6.4 Conclusions for Summer-season Sorghum

Grain yields of up to 7 t/ha in clay loams and 6 t/ha on sandy loams have been obtained with optimum levels of inputs, primarily fertilizers and irrigation. The optimum fertilizer level is 80-150 kg/ha N, 45-75 kg/ha P_2O_5 , and 30-45 kg/ha K_2O , the nitrogen being applied in 2-4 splits with 9-16 irrigations. One analysis shows that the

contribution of water and fertility to grain yield was 1.1 t/ha (irrigation without fertilizer), 2.3 t/ha (80 kg/ha N with restricted irrigation) and 4.9 t/ha (80 kg/ha N with irrigation at 20% of available soil moisture depletion). Presumably P and K were applied to all plots.

It has been suggested that there is scope for inter-cropping irrigated groundnut with sorghum in the summer season.

7. SUGGESTED AREAS OF FUTURE RESEARCH

7.1 Gaps in Published Research Data

There is considerable published research information on yield responses to fertilizers. However, it is not yet possible to correlate, interpret, or account for the reasons behind wide variations in yield responses observed in a given soil-climate complex, even for the same cultivar of sorghum, or to arrive at a prediction equation based on soil, environment, and plant parameters. Averaging hides more than it reveals. There seem to be six main reasons for this situation.

1. We have only a sketchy understanding of the soil and plant nutrition relations in the Indian SAT.
2. Much previous research data concerns irrigated sorghum, while 95% of the crop is grown under rainfed conditions where it receives little fertilizer.
3. Many researchers fail to record and report factors that affect response to fertilizer, such as the status of available nutrients, the depth and moisture status of the soil profile, and the seasonal rainfall and its distribution in relation to physiological stages of the crop's growth.
4. Little research has been done on sorghum fertility on a cropping systems basis.
5. There are few published data on the effect of soil moisture conservation on responses to fertilizers.
6. Data about soil and crop management practices, including irrigation treatments, are inadequately reported.

In future research, all such missing links should be corrected so that the data obtained can be meaningfully interpreted and correlated across locations wherever possible.

7.2 Specific Suggestions

7.2.1 Experiments on the seasonal turnover and mineralization of soil N should be undertaken to assess the amounts of potentially-available N, its dynamics with the distribution of rainfall, and the means of conserving it in the root zone for crop use. A minimum data set should be collected and reported for each experiment, to permit some useful conclusions to be made.

7.2.2 There is a need to obtain more information on crop recovery of added N from ^{15}N measurements, in order to construct balance-sheets of N in agriculture in

the SAT. These should provide data on the N applied to sole-cropped sorghum as well as that which, in intercropping, finds its way into the (legume) intercrop. A network of such experiments on Vertisols and other important soils should be established in different sorghum-growing agroclimatic areas.

7.2.3 The postrainy-season cropping system, primarily based on the use of stored soil moisture, seems to offer near-ideal field conditions for studying the balance and recoveries of added N and the interaction between moisture and fertility, and for generating the set of base data for use in nitrogen modeling. Nutrient modeling will become increasingly important because it is virtually impossible to conduct prolonged research under each and every type of situation. Information is needed on the recovery of different forms of N from different depths and their relation with soil moisture and root systems; and an evaluation of methods of fertilizer placement, perhaps preceded by a multidisciplinary group discussion, is required.

7.2.4 If fertility research is to make a contribution to sorghum production, fertility should always be studied integrally with moisture and extra attention should be paid to factors affecting crop stand. Strong research collaboration should be developed in the areas of (1) soil fertility and soil physics; (2) soil fertility and plant physiology; (3) soil fertility and agroclimatology; and (4) soil fertility and microbiology.

7.2.5 The range or variability of fertilizer responses observed in the rainy season comprise a challenge in research techniques. There is a need for data interpretation, whether through multiple regression or other means, incorporating the variables associated with rainfall distribution, soil physical properties, native and applied fertility, and the past history of the experimental plots.

7.2.6 Research is needed to quantify those aspects of rainfall, poor drainage, and cloudy weather that appear to reduce yields. In many studies, for instance, lower yields were obtained in years of high rainfall, and the expected unconditional positive relation between rainfall and grain yield seem to be an oversimplification of the issue. In certain situations the agroclimatic system that provides more water also reduces solar radiation for photosynthesis, and can also create problems of drainage, leaching, or pest and disease attack that reduce yields.

7.2.7 Research shows that HYCs outyielded traditional cultivars at all levels of management. Selection for yield should therefore be made within two levels of inputs and management. Breeding for higher yield via a higher harvest index, thus insuring more efficient use of the absorbed nutrients for grain production, now appears to be a recommended research approach.

7.2.8 Research into the nitrate form of N and into the suitability of different multinutrient carriers, particularly the NP/NPK types, needs to be undertaken.

7.2.9 The plant character affected most by fertilizer application was the increase in number of grains per panicle. Research into the physiological-nutritional aspects that affect this parameter, the steps necessary to exploit its full potential, and identification of stresses that may reduce the sink size, would be useful.

7.2.10 There is a need to increase our knowledge of the role of potassium and sulphur in sorghum nutrition.

7.2.11 Some information is available on the differential response of sorghum genotypes to the stresses of Zn and Fe, but no stress has been investigated in detail. Two lines of research in this area seem to be desirable.

1. To shift emphasis from single-factor to multifactor screening for possible practical application.
 2. To move (in stages) from solution culture to greenhouse work and then to field experimentation.
- Tolerance of stresses may also be related to rooting patterns, but little research has been done in this area.

7.2.12 In the Coordinated Project on Micronutrients nearly 60000 soil samples have been analyzed, but Maharashtra state (40% of India's sorghum area) has not been covered and progress in Karnataka is slow. It is

desirable that this work be completed so that additional useful information on the micronutrient status of the soils of the Indian SAT will become available.

7.2.13 Limited research on sorghum has been carried out by the Soil-test Crop-response Correlation Project, but this relates to irrigated Sorghum only. Soil fertility evaluation and correlations, as available from this project, are increasingly needed for rainfed sorghum. It is also necessary to find out why one plot of a sorghum hybrid, in producing 1 t/ha grain, removes 22 kg/ha K₂O while another, on similar soils, removes 52 kg/ha K₂O.

7.2.14 Wider testing of the nitrate + ammonium test of N for sorghum, and the possibilities of using electro-ultrafiltration (EUF) measurements for K and other nutrients, appear to be useful areas of research in the SAT.

7.2.15 Some descriptions of soils and climate are available from dryland research centers. It may be useful to establish some long-term fertility experiments at well-documented benchmark sites where detailed monitoring may be undertaken.

7.2.16 There is now sufficient basis to suggest that fertilizer experiments on farmers' fields, conducted under rainfed conditions, should be planned to include recommended extension packages developed for dry-land agriculture.

7.2.17 Finally, it is considered there is a need for an international meeting on various aspects of soil fertility research in the SAT. Its objective would be to identify and schedule research priorities and cooperative programs, including recommended components for interdisciplinary action.

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APPENDIXES

Appendix 1. Sorghum varieties recommended for different states (ICAR 1980).		
States	Hybrids	Varieties
RAINY SEASON		
Maharashtra	CSH 1.CSH5, CSH 6	CSV 3, CSV 4, CSV 5
Karnataka	CSH 1, CSH 2, CSH 5, CSH 6	CSV 3, CSV 4, CSV 5, SB 1066
Andhra Pradesh	CSH 1.CSH 5, CSH 6	CSV 1, CSV 3, CSV 4
Madhya Pradesh	CSH 1.CSH 5, CSH 6	CSV 3, CSV 4, CSV 5, CSV 6
Rajasthan	CSH 1, CSH 5, CSH 6	CSV 3, CSV 4, CSV 5, CSV 6
Gujarat	CSH 1.CSH 5, CSH 6	CSV 3, CSV 5, CSV 6
Uttar Pradesh (Bundelkhand region)	CSH 1.CSH 5, CSH 6	CSV 4, CSV 6
Tamil Nadu	CSH 1, CSH 5, CSH 6	CSV 4, CSV 5
POSTRAINY SEASON		
Maharashtra	CSH 7R, CSH 8R, CSH 1	M 35-1, SPV 86
Karnataka	CSH 1.CSH 7R.CSH8R	M 35-1, SPV 86
Andhra Pradesh	CSH 1, CSH 5, and CSH 6 for <i>maghi</i> CSH 7R, CSH 8R, for <i>рати</i>	CSV 4, <i>Moti</i> for <i>maghi</i> , SPV 86 for <i>rabi</i>
Tamil Nadu	CSH 1, Kovilpatti Tall, CSH 5, CSH 6, CSH 7R and CSR 8R	CSV 4, CSV 5, CO 21 (Tall mutant of 148) and CO 22
Gujarat	CSH 1.CSH 7R,CSH 8R	SPV 86
SUMMER-SEASON IRRIGATED		
Tamil Nadu	CSH 1.CSH 5, CSH 6	CSV 1, CSV 5
Karnataka	CSH 1, CSH 5, CSH 6	CSV 1, CSV 5
Andhra Pradesh	CSH 7R, and CSH 8R	

Appendix 2. An abstract profile of 24 districts which account for 50% of sorghum area in India.

District	Mean ¹ annual rainfall (mm)	Sorghum area (000 ha)	Soil fertility ² N-P-K	Level of N+P2O5+K2O consumption (kg/ha) ³	Testing laboratory
Solapur	678*	574	L-M-H	12	-
Ahmednagar	622*	565	L-M-H	22	-
Osmanabad	810*	540	L-M-H	7	-
Bijapur	553*	514	L-L-H	8	-
Pune	661*	499	M-L-H	15	+
Aurangabad	726*	484	L-M-H	15	+
Parbhani	854	393	M-L-H	8	+
Bhir	685*	383	L-M-H	6	-
Mahhoobnagar	707*	317	L-L-M	24	+
Gulbarga	702*	305	L-L-H	3	+
Kurnool	622*	288	L-L-M	33	-
Akola	801*	284	L-L-H	13	+
Nanded	901*	282	L-M-H	12	-
Yeotmal	1096	281	L-L-H	13	-
Buldhana	893	264	L-M-H	22	+
Dharwar	691*	242	L-L-H	21	+
Adilabad	1051	239	M-L-H	7	+
Jalgaon	787*	238	L-M-H	49	+
Satara	1025*	235	L-L-M	30	-
Raichur	602*	223	M-L-N	38	+
Sangli	568*	221	M-M-M	27	-
Khammam	1016	220	L-L-H	22	+
Chandrapur	1267	218	L-L-M	10	-
Nagpur	1242	216	L-L-M	27	+

Notes: 1. Weekly probabilities of rainfall available for districts marked with an * (Virmani et al 1982b)

2. Low, medium and high ratings (Source IARI 1980b.)

3. Overall mean consumption, 1978-80 period.



ICRISAT

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